Locating Abandoned Mines Using the Active Mining Operation as the Seismic Energy Source – Demonstration of a New Method

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Abstract

This study demonstrates a new method for detecting the margin of old mine works using the seismic energy generated by active mining in the coal seam. As the first test of this new concept, the method should not be viewed as a proven, off-the-shelf technology, but rather a demonstration of the fundamental concept which has promise for detecting the margins of old mine works. For the primary method a linear spread of vertical 4.5Hz geophones on the earth's surface was distributed across the margin of old mine works (both flooded and air-filled locations) and to a position over the active mining nearby. The seismic vibrations associated with the underground mining were passively recorded across this spread, with individual records as long as 32 seconds. Through a process of crosscorrelation, using each seismic trace sequentially as the pilot sweep for correlation with each other trace in the recording, two distinct seismic wave arrival patterns emerged from the data. The direct arrival from the mining operation to the surface through the rock overlying the coal seam was distinct and well represented in

all processed data sets. However, in the data sets across the flooded mine site an additional distinctive signal was observed in correlated data in the vicinity of the margin of the old mine when a seismic trace in that vicinity was used as the pilot sweep for correlation. This distinctive signal apparently represents seismic energy scattering to the surface from the termination of the coal seam at the mine margin. This scattered signal is apparently absent in the data collected at the dry mine site, however. Whether this is as a result of the in-seam seismic energy at the dry mine location being dominantly reflected back along the coal seam (i.e., a planar vertical coal/air boundary of high impedance), or some other cause preventing the conversion or transmission of seismic energy toward the surface at this site, is unclear. The strong 14-15Hz periodic signal present in the seismic waves scattered to the surface from the wet mine margin is also observed in data recorded by an in-seam seismometer. This low frequency in-seam signal is apparently a Rayleigh-type wave but not an Airy phase; perhaps instead a signal enhanced by the nature of the continuous miner source's particular coupling with the coal seam. A test of a secondary method to detect old mine works using the attenuation of refraction arrivals from refractors deeper than the coal seam also shows promise.

Introduction

The project described here demonstrates a new method for detecting the margin of poorly mapped old mine works using the seismic waves generated by the active mining of the coal seam. This method resembles that of "seismic while drilling" (Poletto, et al., 2004) and especially "forward looking seismic" (Howell, et al., 1998; Hauser, 2001), and seeks to detect at the surface the seismic signal scattered when in-seam seismic waves generated by mining operations encounter the disruption of the coal seam at old mine works. The key attractive features of this method are that it operates entirely on the earth's surface and it requires active mining. Consequently, the method has no negative impact on or interruption of underground mining operations; in fact, just the opposite -- ongoing mining is a fundamental part of the method.

The fieldwork was conducted near Georgetown, IL, (Figure 1) at the Vermilion Grove mine complex of the Black Beauty Coal Company, now part of Peabody Energy. The mine personnel were extremely cooperative and helpful in the course of this study, providing land survey information and subsurface maps, assistance with gaining land access, and provided details of the location and timing of underground operations during the periods of surface seismic recording. Through discussions with the mine personnel two demonstration locations were identified southwest of Georgetown, Illinois, (Figure 1) where active mining was approaching closed mine works, one flooded and one air filled. The flooded Bunsenville Mine (closed about 1947 and known to be flooded in this southern part of the old works from previous drilling reported by mine personnel) provided the wet mine void setting, whereas the current Vermilian Grove mine (at a location closed two years previous) served as the dry mine void example. We also recorded in-seam seismic energy associated with the mining operation using a 3-component borehole seismometer, and evaluated a secondary method using waves emerging from deeper refracting layers to determine to what extent they might be attenuated by old mine works in comparison with adjacent areas with an intact coal seam. Figure 1 shows the location of more detailed maps of these demonstration locations, which are described further below.

Primary Method – In-Seam Wave Scattering

The primary method of this study uses the active mining in a coal seam as the source of seismic energy for the detection of old mine works. This is a completely new seismic approach in that conventional in-seam or surface seismic methods consider the mining-generated seismic waves to be 'noise', i.e., unwanted background seismic signals. In contrast, by using the mining-generated seismic energy the method demonstrated here *requires* active mining in the vicinity of the location being examined. Consequently, unlike conventional underground controlled-source in-seam methods, no interruption of mining operations is necessary. Moreover, no simultaneous underground recording of a signal at the source of active mining is necessary. In the method demonstrated here crosscorrelation processing is used to extract from the passive recordings at the surface any converted seismic signals that scatter or emanate from the location where in-seam waves encounter the margin of old mine works. Detailed characterization of the signal at the active mine face or the inseam wave itself is not necessary.

Anyone who has ever seen modern underground coal mine operations is keenly aware that significant seismic energy is generated at the active face. The resulting seismic waves generally radiate away from the active face in two main pathways in the earth. One pathway is directly to the surface through the rock overlying the coal seam. These waves consist of both compressional (P) and shear (S) waves that arrive at the ground surface via a direct path (Figure 2). These direct waves will travel through the overlying rock at the P- and S-wave velocity of the rock and will become more emergent aves (i.e., coming out of the ground at an increasingly shallow angle) at greater distances with an associated decrease in amplitude. The P-wave seismic velocity of the overlying sedimentary strata of Pennsylvanian age can be 9,000-11,000 ft/s whereas the P-wave velocity of coal can range from 5000-7500 ft/s (i.e., 1600-2400m/s) (Dombrowski, et al., 1994; Dresen, et al., 1994). The second main pathway for seismic energy generated by mining equipment is along or within the coal seam away from the active face. These in-seam waves are largely guided or refracted within and along the coal seam due to the low seismic velocity of the coal relative to the rocks above and below (Evison, 1955, Dombrowski, et al., 1994; Dresen, et al., 1994). The main in-seam waves generated are equivalent to the surface waves called Rayleigh waves (vertical polarization) and Love waves (horizontal polarization), and similarly become dispersive with distance and time (Krey, 1963). As these in-seam seismic waves encounter a disruption of the coal seam, such as old mine works, some of the in-seam wave energy can be reflected back within the seam (e.g., Krey, 1963) or can be converted to other seismic waves that can radiate to the ground surface above. The primary method described here is devised to detect the scattered P-waves converted from the in-seam seismic waves at the disruption of the coal seam, and thereby identify and locate the margin of old mine works.

One of the most powerful processes of seismic data processing is that of crosscorrelation. Crosscorrelation is a fundamental process of digital signal processing and is the operative process in the vibroseis seismic method (i.e., Baeten and Ziolkowski, 1990). Vibroseis, originally developed by Conoco, Inc., has been used extensively in the hydrocarbon industry since the 1970’s. In the vibroseis method a vibrator truck generates and radiates into the ground a controlled series of seismic waves of a specific range of frequencies for a specific period of time, called a sweep. The wave train of the vibroseis sweep travels into the earth, reflecting and refracting at boundaries, eventually arriving at a series of surface seismic sensors or geophones where they are recorded. In vibroseis, the seismic trace recorded at a geophone contains many superimposed wave trains of the original source sweep that took different paths in the earth and arriving at different delayed times. When the recorded data are cross-correlated with the seismic sweep originally generated at the vibrator truck the result is a new wave form or time series consisting of zero-phase wavelets representing the correlation coefficient of these two time series. The "seismic-while-drilling" method (Poletto, et al., 2004), is similar to vibroseis in that it uses a special recording of the vibration at or near the drill bit to use as the pilot sweep for correlation with data recorded at geophones at the surface.

This crosscorrelation method as applied in this study is different from vibroseis and seismic-while-drilling in that no source-specific wave train, or source sweep, is recorded at the site of the mining operation for subsequent correlation purposes. None is needed. Instead, the seismic signal recorded at each geophone at the surface is sequentially used/tested as a pilot sweep and cross-correlated with all the other traces of that record to search for a spatially distinct signal, shifted only slightly in time from one seismic trace to the next, and which has a subsurface source location spatially separate and distinct from that of the active mining operation in the distance.

Figures 3 and 4 help demonstrate the concept of crosscorrelation. Consider a seismic wave train starting from a single subsurface point (i.e, an earthquake, or the location where the in-seam seismic waves encounter the old mine) and radiating to the surface where a series of seismic sensors (Figure 3A) detects and records the arriving seismic wave train (Figure 3B). The recording box starts collecting data at all locations at the same time (t_0 in Figure 3B) for a span of time (4-32 seconds, for example). The wave train emanating from the subsurface point arrives at slightly different times at each of the surface sensors (t_1, t_2, . . .) depending upon the distance the wave traveled and the velocity of the material along its path. The time these particular wave trains departed the source ($t_{scatter}$) is not evident in the data but could be either before or after t_0 in time. The similar wave trains arriving at each of these seismic stations and shifted slightly in time are evident in this schematic example, but commonly the wave train is mixed with other ambient noise and indiscernible to the eye.

Crosscorrelation is a mathematical process that measures the extent that two time series' such as seismic records are similar. For an analogy, think of suspending two white strings by their ends, one from each hand. Each white string is of the same length with identical color markings along their length. When one string is held higher or lower than the other, there is little if any correlation between the markings from one string to the other, i.e., a low correlation coefficient. However, when the two strings are brought to the same level the markings on each one line up exactly and there is a direct correlation from one to the other. This is a perfect correlation, or a correlation coefficient of 1, and also is called an autocorrelation (since it represents the crosscorrelation of a series with itself). Now tie a short red string to the top end of one of the two white strings and hold this new string from the end of its red addition. When you bring your hands to the same level this time there is a very poor correlation between one string and the next; the second white string is now hanging lower by an amount equal to the length of the red string attached. However, if you proceed to shift the white string along and adjacent to the other red+white string you will continue to have a poor correspondence or correlation between what markings are on each string, until the white string is shifted exactly the length of the red one. At that shift both strings will have a high correlation between one another, i.e., a high correlation coefficient, but at a shift equal to the amount you had to shift the two strings from level.

This is conceptually what we are doing when we cross-correlate the seismic wave trains recorded at a series of closely spaced seismic sensors at the surface. By using one seismic record 'string' from one location and shifting it in time in relation to all the other nearby seismic record 'strings' we determine the extent to which that record correlates with the others at a series of small sequential time shifts. Any weak but essentially identical wave trains shifted slightly in time and arriving from a local scatterer in the subsurface (Figure 3A and B) will show up as a strong correlation coefficient value that shifts from one correlated record to the next (Figure 4A). The relative pattern of correlation coefficient time shifts among a set of seismic traces will remain fundamentally the same from one to another regardless which one is used for the crosscorrelation, with the overall pattern collectively shifting up or down depending upon which is the correlation operator whose autocorrelation defines the zero time shift (Figure 4A and B).

The wave train we are trying to detect in our data through the process of crosscorrelation is that which is generated at and emanating from the margin of the old mine workings as a result of the conversion of the in-seam seismic waves. Therefore, the exact seismic characteristics of the signal generated by the mining machinery in the coal seam, at or near the working face, is not particularly important, only that significant in-seam seismic energy is being created by that mining. In fact, the effect of dispersion of seismic energy in the coal seam wave guide should significantly modify the signal generated at the active face such that it would not resemble in detail the wave arriving at the mine margin. The method we are using here strongly resembles, and expands upon, that of the "forward looking seismic" method (Howell, et al., 1998; Hauser, 2001) that used similar passive surface recordings of vibrations from a tunnel boring machine to identify obstructions nearby and ahead.

Wet Void Demonstration

The wet void demonstration was conducted across a level open field approximately 1.5 miles southwest of Georgetown, Illinois, (Figures 1 and 5) using a linear spread of 120 individual 4.5 Hz geophones placed vertically at a spacing of 15 feet. Station 1 (Northing 1,201,511.96, Easting 689,969.37) was located approximately above the location of the active mining at that time, with station 120 (Northing 1,201,467.53, Easting 688,320.11) located to the west well into the area underlain by the Bunsenville Mine (Figure 5). The Bunsenville Mine was closed in 1947 and staff of Black Beauty Coal Company indicate that it is flooded in this area based upon drill holes elsewhere in this southern area of the old mine. This was later confirmed during confirmational drilling for this project when water rose to a level about 10 feet below the ground surface in those drill holes that encountered mine void/collapse. The distance from Station 1, above the active mining, to the anticipated eastern margin of the Bunsenville mine (at about Station 82) is approximately 1200 feet, using the best available information provided by BBCC of spatially registered scans of old mine maps (Figure 5).

The recording system at this site consisted of two, 60-channel StrataVisor seismic recorders, cables, and 120 OYO 4.5 Hz vertical geophones. The StrataVisors were placed in the middle of the spread (between stations 60 and 61) with one recording the data at ground stations 1-60 and one recording ground stations 61-120. Both StrataVisors were manually triggered simultaneously using a plunger switch and a trigger-wire splitter. The result is an effective 120-channel recording system. The 32-second data records were collected at a sample rate of 0.5 ms, which resulted in a Nyquist frequency of 1000Hz, well above the likely frequencies of interest. The response of the 4.5 Hz geophones is flat at higher frequencies. The ambient seismic signal could be watched on the StrataVisor displays in real time, and periods of mining activity could be easily recognized for manual triggering of the recording systems.

To remove any ambiguity about where mining was occurring underground in relation to the passive seismic recordings at the surface, a subsurface observer with a synchronized watch recorded details of the mining operations below during a pre-defined time window during which the passive seismic data were being recorded on the surface. This information, although not fundamental to the process or method itself, allowed us to assess to what extent the relative mining directionality (entry vs. cross-cut) or location within the 360 foot wide front represented by the 7 entries at this location, would impact the results. The in-seam seismic signal at or near the mining equipment is not necessary for this new method, therefore no seismic recordings were made in the subsurface at the active face.

Wet Void Results

Inspection of the raw data (Figure 6) confirms what was clear on the StrataVisor displays in the field, that a strong mining-generated signal is present in the data. This signal is expectedly most prominent at the stations closer to the mining, and individual pulses commonly can be traced across most of the 120 recording channels (1800 feet). These impulses clearly represent rapid episodic direct-wave arrivals traveling in the rock overlying the coal seam and associated with the mining process. These individual direct arrivals in the raw data individually have the expected time/distance move-out indicating a P-wave velocity of ~10,500 ft/sec for the rock above the coal (compare Figures 2 and 6).

In a few instances a series of rhythmic and repetitive seismic waves can be observed in the raw data, and define a distinctive oscillatory concave downward pattern on the data display (Figure 6). This pattern, when it occurs, usually is evident for a few seconds after a period of strong direct arrivals in the data associated with very active mining and notably also occurs spatially in the immediate vicinity of the likely margin of the old works of the Bunsenville Mine (Stations 70-90, Figures 5 and 6). The location and arrival time variation (move-out) of this oscillatory seismic signal is like that expected from waves radiating from a particular location beneath (i.e., Figure 2). The correlation processing, described below, strongly accentuates these two patterns in the data.

Correlation Processing

Standard preprocessing of all the data records includes removal of any DC bias, de-spiking to remove noise spikes that would introduce correlation noise, and a high-cut filter to remove frequencies above 600 Hz.

The primary processing step that is fundamental to the method demonstrated here is the systematic correlation of all the traces in a seismic record, by sequentially using each seismic trace of the record as the pilot trace for correlation with all of the others of that record. This process results in a large number of correlation combinations for each field recording and is therefore time consuming, but it could be substantially optimized and automated for analyzing future data sets.

Figure 7 is an example of one such correlation. In this particular example, trace 62 was arbitrarily used as the pilot trace for correlation. As a result, trace 62 here is an autocorrelation (correlation with itself) and results in a strong zero-phase autocorrelation wavelet at a time defined as 0 seconds for that record. The strong and rapidly episodic series of direct arrivals in the raw data (Figure 6) represents a significant common wave train in most of the raw data traces, and results in a strong correlation between trace 62 and most other traces. The resulting correlation record exhibits a strong zero phase wavelet that shifts systematically in time across the record revealing a velocity of about 10,500 ft/s (Figure 7), which is, as one would expect, the velocity of each of the many impulses seen in the raw data (Figure 6) that contribute to the overall 32 second wave form arriving at each geophone. The same pattern appears regardless which pilot trace is used but diminishes in amplitude when a trace at greater distances from the mining machinery is used (Figures 8 and 9). This is the correlation representation of the direct arrival of seismic waves generated by the mining machinery and arriving progressively later at the geophones across the spread (compare with Figure 2).

Notably, the oscillatory concave downward signal seen in some of the raw data in the vicinity of traces 70-90 (Figure 6) is significantly enhanced in the resulting correlated records when a trace in that range of stations is used for correlation. After correlation this pattern becomes very prominent in this series of traces even for records having no such pattern visible in the raw data. This oscillatory concave downward signal on the time section becomes increasingly strong when the trace used for correlation is between stations 75 and 90 (see Figure 9) and especially when using a trace such as at station 88 near its crest (i.e, Figure 10). Although this pattern shifts up and down in time on the correlated data display depending upon which pilot trace autocorrelation defines zero time; the arched pattern does not shift laterally or change shape, instead remaining spatially fixed with its crest at about station 88. This means that the raw data at stations 70-90 contain a spatially restricted seismic signal or wave train that is substantially common to each, with the relative arrival time of that common wave train defined by the arched pattern of the correlation wavelet. This is also confirmed, as described above, by the same pattern being sometimes observed in raw data records (Figure 6).

In the most straightforward interpretation, where the rock velocities beneath are laterally uniform, the crest (minimum travel time) of this pattern would occur at the epicenter above its source scatterer (see figure 2). If this scatterer is the mine margin, then that margin would be interpreted to lie beneath Station 88. However, Station 88 is 90 feet west of the mine margin as indicated on the mine map originally provided to us by Black Beauty Coal Company. Does this indicate that the mine map is not positioned accurately, or might it indicate that rock velocity effects above the old mine (i.e., collapsed or broken rock above mine works) are distorting the arrival time of scattered seismic energy? To address this discrepancy confirmational drilling was performed to define the margin of the old mine works.

Confirmational Drilling

Drilling to confirm the location of the targeted mine margin at depth in relation to the seismic results confirms that the margin of the mine in an east-west sense is very likely close to that on the map provided by Black Beauty Coal Company. A series of nine boreholes (Figure 11) was drilled at the site by Magnum Drilling of Evansville, Indiana. The driller logs for these holes are included as Appendix A. In each drill hole that encountered old mine works, water rose to within approximately 10 feet below the ground surface, demonstrating these are flooded workings as was expected.

Drilling appears to confirm that the mine margin is likely approximately at seismic station 82; not far from that represented on the map provided by Black Beauty Coal Company. Drill holes WSU-C1, WSU-C2, and WSU-C5 all encountered collapsed works and no coal, a result consistent with their encountering the pair of N-S entries on the eastern margin of the mine map. If this is the case, then the mine map could be shifted as much as 10 feet east from its presently mapped position. However, the map can not be shifted farther east than that because the only place that drill holes WSU-C1 and WSU-C2 could accommodate a larger shift (an E-W entry 40-50 feet south of their present apparent position on the mine map) would force drill hole WSU-C5 to traverse a pillar and just manage to encounter the eastern edge of the western N-S entry at the same time WSU-C3 managed to encounter coal and no collapse just east of the easternmost N-S entry. Also, the row of 5 drill holes at a spacing of 15 feet over a distance of 60 feet (WSU-C3,9,4,8,7) that encounter undisturbed coal can not be accommodated anywhere inside the mine plan in this vicinity in any reasonable way (the main N-S pillar just west of the pair of perimeter entries is nowhere 60 feet wide on the old map). Instead, these 5 drill holes are strongly likely to be within the main barrier east of the old mine. In sum, the mine margin is likely located at about seismic station 82. However, this leaves intact the 90 foot apparent discrepancy with the location suggested by a simple interpretation of the seismic data.

Ray-Trace Modeling

The drilling results confirm that the mine works are clearly as far east as WSU-C2 (5 feet west of Station 82), yet the apparent location of the subsurface seismic scatterer as based upon a simple minimum-time interpretation of the correlated seismic results would place the margin at about seismic station 88 -- a discrepancy of about 90 feet. A 90 foot mis-location for the mine margin using energy generated by mining 1200 feet away using passive sensors on the surface may not be substantial when only its detection is desired, which can then be followed up by drilling or other methods. However, since in a simple layered earth the minimum travel time for scattered seismic waves from the mine margin would be anticipated at the epicenter directly above the mine margin, it is important to understand the possible cause of the discrepancy.

One way one might explain this minor lateral discrepancy is through the presence of brecciation in the rock above the old mine that produces slower velocities there which affect the travel time of seismic waves radiating upward from the mine margin. In addition, vertical zones or chimneys of low-velocity broken rock locally above the mined area are not only plausible, but likely. Any local zones of lower seismic velocity due to collapse, brecciation, and weathering would refract and change the travel time of seismic energy, perhaps enough to result in a shift in the location of the minimum-time crest seen in the correlated seismic data. This possibility is explored below with a simple ray-trace model. Although this is but one of many similar variations of plausible forward models that could be constructed, and the velocity structure shown should not be considered completely resolved, however, the model is constructed with several important constraints. Drilling has helped constrain the likely location of the mine margin, which together with the depth of the coal seam and mine are constraints in the model. The lateral relative variation of travel times for scattered energy, as determined from our seismic data analysis, is another constraint that must be met in any successful ray-trace model. Drill holes during the confirmational drilling revealed that (at least on the scale of an individual drill hole sample of the subsurface) the collapse and rubble over the old mine works rises locally at least 20 feet above the original top of coal. This does not say that in places not drilled that the stoping or brecciation did not continue even higher. From the reports from farmers locally of continuing surface sagging and newly formed areas of poor drainage in the farm fields over the Bunsenville Mine, it is highly likely that significant brecciation and associated variation of seismic velocity of the rock layers has occurred between the old mine and the bedrock surface. What is being tested in the ray-trace model is (1) a model that meets the specific constraints mentioned above, which (2) uses plausible variations and distributions of seismic velocities that are consistent with the setting of a collapsing bedrock over a 60 year old flooded mine with sparse pillars. Although some poorly constrained details of the model, such as the details of the low velocity chimneys shown, should not be seen as proven fact, the process of constructing the model should be viewed as an attempt to demonstrate how localized zones of higher and lower seismic velocity related to the rock fragmentation above a collapsing mine (as is, in fact, expected and happening) can change rock velocity and thereby the location of the minimum travel time at the surface of scattered energy radiating from the mine margin. Again, the resulting model should not be considered ground-truth for the specific details of rock velocity distribution used to make the resulting travel times fit those observed in our seismic data set; however, it does demonstrate that seismic velocity variation in the collapsing rock above the old mine can have a marked effect upon any mining-related seismic energy emanating from the old mine margin, and could be the explaination why the minimum travel time for the seismic energy emanating from the margin of the old mine appears to occur 90 ft west of the margin as confirmed by drilling.

The ray trace modeling was performed using a program called MacRay (Luetgert, 1992), which is merely the most recent incarnation of a ray trace modeling package developed over 20 year ago by and for the US Geological Survey for modeling crustal scale seismic refraction data sets. Within a model, interfaces are defined based initially upon first order geologic constraints, with any pair of successive interfaces describing a model 'layer'. Additional layers are added as needed to characterize the velocity structure being modeled. Within a layer the velocity may be defined in terms of the velocity at the top and bottom of the layer and the velocity can vary vertically and laterally within a layer. Layers and velocities are varied in the model to reflect the conditions and variations observed or inferred in the earth model being studied. A series of rays are then 'shot' or propagated from a source location at a range of initial angles to find those range of rays that successfully reach the surface. Iterating and refining the range of angles of the rays examined and to examine changes

The goal of the modeling is to find a plausible earth model that meets the required constraints, but which provides the appropriate range of travel times for the arrival of seismic energy at the surface in comparison with observed variations of seismic data there. Through an iterative process the model layers and/or velocities are varied and rays reshot in the attempt to find a plausible and constrained model that results in the surface arrival time of the rays in the model to match those observed in the data. This is by definition a forward modeling process, not an inversion process.

For our model the source point was the old mine boundary in the subsurface, and the variation in arrival time across the surface had to closely match the variation seen in our seismic data. In the model the variation of velocities for the rock layers above the old mine approximated one or more collapse and brecciated zones of significant vertical extent with less brecciated zones between. The vertical stoping and brecciation and the associated velocity variation are plausible conditions in this geological setting.

Figure 12 is a ray trace model in which seismic P-waves radiate from the mine margin at station 82, the mine margin location where they were converted from in-seam waves. As this model shows, it is possible to shift the location of the minimum arrival time for waves arriving at the surface significantly to the west (i.e., to station 88) as a result of a vertical zone of broken rock of slower P-wave velocity. The full vertical and lateral extent of fracturing of the rocks above the old mine cannot be know in detail from the series of nine drill holes, but significant collapse was encountered in drill holes WSU-C1,2,5 (Appendix A). Also, the mine map indicates that very few small pillars were left in the course of mining in this part of the old mine (Figures 5 and 11). The farm fields over the mined area exhibit broad areas of subsidence that indicate significant subsurface collapse on a broader scale. Clearly, significant fracturing of the rock overlying the old mine is present, and likely occurs over a broad area above the old mine, and local columns of fractured rock could be present. The model shown in Figure 12 demonstrates a plausible way for variations in seismic velocity associated with local fracturing and collapse to explain the 90-foot lateral shift of the minimum travel time of waves scattered from the mine margin beneath Station 82. Other model variations might be constructed and tested, but this model demonstrates that local zones of slower velocity fragmented rocks above the mined area can possibly explain the westward shift of the surface location of the minimum travel time of seismic waves scattered from the old mine margin.

The Effect of Miner Location and Direction

The data at the wet void site are found to contain the seismic signatures described above regardless of mining orientation. Figure 13 shows correlated records for data collected when the direction of the mining was at 90 degrees different (see Figure 5) -- one to the NW in the direction of entry advance toward the old mine works, and one toward the NE in the direction of a cross-cut largely away from the old mine works. Both correlated records reveal the stong reverbratory signal at the mine margin, although the correlated record of the data when the miner was directed to the NE in the cross-cut exhibits a chattery appearance in comparison with the one directed NW. This might suggest the additional presence of a short-path multiple of in-seam waves from the adjacent mine entry to the NE, a signal which could therefore also be present in the converted waves radiated from the mine margin to the surface. Regardless, it is clear that at least in this setting and in these data the orientation and position of the miner have little effect upon the presence of the main pattern of conversion and scattering observed emanating at the old mine margin.

Dry Void Demonstration

The dry void site is located about 3 miles southwest of Georgetown, Illinois (Figure 1). At the time of the deployment of the seismic equipment, the active mining was much closer to the old mine works, approximately 600 feet (Figure 14). The seismic line was positioned along the margin of a farm field across level ground in a linear spread of 60 stations at a 10-foot spacing with a single OYO 4.5 Hz vertical geophone at each station. Station 1 was positioned in the area generally above the active mining and station 60 was positioned well to the east of the margin of the abandoned mine (Figure 14). The margin of the old mine lay approximately under seismic station 41. The pre-processing and correlation of these data followed that described above for the wet mine data.

The correlated results at this site (Figure 15) show a prominent direct arrival similar to that observed at the wet mine site; however, in these data there is a notable lack of a distinctive pattern of signals in the data, either in the raw data or after correlation, which might be relatable to the old mine margin.

There are several factors that can contribute to the conversion and scattering of seismic energy (Figure 16). One factor is the void boundary orientation and shape (Figure 16A.). A vertical planar boundary perpendicular to the coal seam would be expected to not scatter significant energy toward the surface. Instead, this orientation and shape would be expected to reflect energy significantly back along the coal seam. If instead the boundary is irregular, one would expect more of the incident seismic energy to convert to other seismic phases and be scattered away from the coal seam and perhaps to the surface. Another factor is the magnitude of the impedance contrast between the coal and the material occupying the old mine (Figure 16B.). The seismic impedance contrast between coal and air (large difference of density and velocity) is significantly greater than that between coal and water (smaller difference of density and velocity). As a result, more of the in-seam seismic energy encountering the boundary of an air-filled void would be expected to reflect back into the coal seam than for a water-filled void. The larger fraction of seismic energy continuing through the lower impedance boundary with the water-filled void, continuing as converted P waves, would also have the increased opportunity to scatter to the surface within the old mine complex. A third factor would be the presence of collapsed material in the old mine and the associated irregular roof (Figure 16C). The presence of collapsed material and roof fall provides additional interfaces for the scattering of seismic energy, with increased likelihood that some of that energy is directed toward the earth's surface.

The wet mine example described above is an example where all three factors are likely present. The old Bunsenville mine where our seismic study and drilling encountered it is flooded, significantly filled with collapsed material, with broken rock, rubble, and voids seen in drill holes to extend upward at least 20 feet above the top of coal. In this setting we found significant mining related seismic signal being scattered to the surface from the margin of the old mine. In contrast, at the dry mine site we studied the mine void was air filled and was only 3 years old at the time of our seismic study and consequently much less likely to have experienced collapse. The lack of clear scattered seismic energy detectable at the surface above the young dry-mine margin, might either mean that most of the mining related in-seam seismic energy there is reflected back within and along the coal seam, or that some condition between the mine margin and the surface has attenuated the scattered signal. Although the absence of evidence is not evidence of absence, these results may indeed suggest that young, air-filled mines are not easily detected with this new method; however, young air-filled mines pose less risk than flooded mines and younger mines are also likely better mapped.

In-Seam Seismometer

An ancillary part of this study was to install a seismometer in the coal seam to characterize the seismic waves associated with the active mining operation. The seismic waves expected to be scattered to the surface from the old mine margin would be converted from the seismic waves traveling in and along the coal seam and therefore will be fundamentally different than the seam waves. Also, the ability of the method being tested here to locate the position of the subsurface scatterer (mine margin) is dependent on the recognition of the scattered wave train common among several adjacent recordings in the vicinity of the scatterer, and not directly dependant upon knowing the detailed nature of the waves in and along the coal seam. However, the waves scattered to the surface are the result of the interaction of the mine margin with the wave energy in and along the coal seam, so a better understanding of the nature of mining-related seismic energy in the coal seam potentially could provide insights into how the conversion process at a mine margin occurs.

The initial effort to install a borehole seismometer failed. We grouted the seismometer into place in the coal seam but the seismometer ceased working before useful data could be recorded. Another borehole seismometer was later installed at a different location near an area of active mining (Figure 17). The timing and location of this deployment and data collection was not coincident with any other part of this project and not in the vicinity of any old mine margin, so direct comparisons can not be made between the in-seam signal observed and any surface seismic observations of converted waves scattered to the surface. However, the data still can potentially provide some insight into the seismic waves in the coal seam related to nearby active mining in the seam and the ultimate source of energy for the converted waves that scatter to the surface.

The seismometer deployed was a Geospace Technologies GS20DX 10Hz 3-component seismometer with 395 Ohm coils and a 2400 Ohm resister (50% damping) for each element. The specifications for these 10 Hz elements exhibit a flat response to frequencies higher than 250Hz and a harmonic distortion of <0.2%. The elements are encased in a 1.8 inch diameter stainless steel waterproof cylinder with a pair of downward-angled spring clamps mounted on one side. For deployment, these spring clamps are held depressed against the side of the seismometer by a wrap of masking tape as the seismometer is lowered to the desired depth, where a high-tensile fine line that was looped under the tape is pulled to tear the tape and deploy the springs, which then clamp the seismometer to the side of the borehole. A tape measure attached to the seismometer provided detailed depth information for positioning the seismometer at the desired location for installation.

With this type of seismometer and deployment, once it is securely clamped into the borehole the actual orientation of the two horizontal components must be established. At the surface and 35 feet east of the borehole we used a shear wave hammer source to generate a N-S polarized impulsive shear wave signal with first motion toward the south and recorded the signal with the seismometer at a depth of 250 feet. The signals received at the two orthogonal horizontal components (H1 and H2) of the seismometer were then trigonometrically rotated at increments of 10 degrees to a new coordinate system. Using the N-S polarized shear wave at the ground surface, the horizontal components of the seismometer were found to be within 10 degrees of being aligned with N-S and E-W. The H2 component was found to be positive to the East and the H2 component was found to be positive to the South.

The seismometer was installed between the top of coal and the middle of the seam (i.e., ¼ the distance down from the top of coal). This location was chosen because it would provide information for both the Love and Rayleigh seam waves. The Love waves, having horizontal particle motion perpendicular to the direction of travel theoretically have maximum amplitude in the middle of the seam and decrease toward the upper and lower margin. The Rayleigh waves have maximum amplitude near the top and bottom of the coal and a null in the middle of the seam, and have a prograde circular particle motion in the plane perpendicular to the coal seam in the direction of travel.

Consequently, by placing the borehole seismometer half way between the top and middle of coal, we anticipated detecting both wave forms.

Data were collected using a Strataview seismic recorder at a sample rate of 0.5ms. These 2000 samples per second correspond to a Nyquist frequency of 1000Hz for these data. At this sample rate the Strataview is capable of collecting records 4 seconds in length. The real-time display of the Strataview was monitored, and recording was manually triggered both during times of clear strong mining signal and intervening quiet times. The recordings in Figure 18 are representative of mining and non-mining signals.

A comparison of data collected during spans of mining activity and times between (Figure 18) reveals that the mining related seismic energy observed is dominated by a strong ~14Hz periodic signal. This strong signal is evident on both the vertical and H2 (E-W) components, and is nearly absent on the H1 (N-S) component. At the time of these recordings the mining activity was at a location about 700 feet to the ENE of the seismometer (Figure 17). Upon careful examination, the particle motion exhibited in these data is circular and top-to-the-west in a vertical E-W plane away from the site of mining. This particle motion is that which is expected for a Rayleigh-type in-seam wave in the upper half of the coal seam; however, the frequency is lower than that expected for the dominant frequency of such in-seam waves. The Airy Phase for a coal seam of 1m half width (the seam is ~5ft thick at this location) would have a dominant frequency of about 190Hz for Mode 1 waves (Krey, 1963). Frequency spectra for these data (Figure 19) show 14Hz and 22 Hz peaks during active mining, but a lack of anomalous signal at the frequency range expected for the Airy Phase of inseam waves.

The ~14-15Hz periodic signal is also observed in the seismic waves recorded at the surface (Figure 10) which were scattered from the vicinity of the wet mine margin. Clearly a periodic low frequency signal is present in both the in-seam waves associated with mining and also the waves converted and scattered to the surface from these waves. However, where is this strong signal generated/amplified -- in the mining or in the in-seam wave dispersion wave guide?

This strong signal, so far, is apparently inconsistent with any high amplitude Airy Phase as a result of wave guide dispersion; however, it is possible the origin of the signal is with the mining process itself. The dispersion and amplification characteristics of seismic energy in a coal seam wave guide is quite complex and dependent upon not only the seismic velocities and density of coal and bounding rock, and thickness of the seam, but also on how the seismic energy is coupled to the coal. The cutter of the continuous miner rotates at about 30 RPM, and contains several rows of cutting teeth parallel to the horizontal axis of rotation. We speculate that the 14-15Hz signal (and also perhaps the 22Hz signal seen in frequency spectra) is imparted to the coal seam and bounding rocks during the mining process and is not a filtering consequence of the coal seam wave guide. This signal, however, apparently survives the complex conversion of seismic energy at the old mine works and is detectable in the scattered energy observed at the surface.

Secondary Method – Refraction Attenuation

A secondary method examined for mapping areas of old mine works represents a novel use of seismic refraction waves. With a surface source of seismic energy positioned at a sufficiently large distance from a spread of geophones across a mine margin, refraction waves could be generated which would travel along layers deeper than the coal seam and return to the surface across the mine margin. The expectation is that the refraction energy returning to the surface would experience greater attenuation in mined areas than areas with an intact coal seam.

A test of this method was done in the vicinity of the main part of the study described above (Figures 1 and 20). A 48 station spread of individual 4.5 Hz geophones was deployed at a 10 foot spacing N-S along county road N1520E across the margin of a recently mined (air filled) area of the Vermilion Grove mine. A Bison Elastic Wave Generator (EWG) was used to generate seismic energy at 300 foot intervals away from the seismic spread to distances up to 2100 feet. Repeated hits were summed (usually 16-32) to help the signal recorded overcome the ambient noise levels (i.e., windy conditions) at these far offsets. This 48 station spread was also deployed along the E-W along county road 700N across the margin of the Bunsenville Mine less than a mile north of the earlier described wet mine study, and a similar walk-away set of seismic records were collected.

Originally, we planned to use a vibroseis source; however, with the dramatic rise of the price of oil and gas before starting the field work for this project it became impossible to contract for or lease the use of vibroseis equipment. Vibroseis has some inherently beneficial noise mitigating characteristics and allows control of the characteristics of the seismic energy going into the ground, but because of the lack of availability we substituted the weight drop source.

The results with the weight drop source reveal this method has promise. Clear refraction arrivals were recorded from a source offset distance of at least 2100 feet using the EWG (Figure 21). The windy conditions during the dry mine refraction data acquisition, however, resulted in significant noise on the north half of the seismic spread due to blowing trees and bushes. Although wind noise was not as significant during the wet mine refraction acquisition, vehicle related noise was accidentally stacked into the data in the middle of the recording spread (Figure 21). Nonetheless, the first break refraction arrivals on both the wet mine and dry mine recording spreads show a distinct reduction in refraction amplitude of the first break in the area of the mine. In addition, there is a suggestion of a delay in the arrival time for these weak refraction first break arrivals, especially for the wet mine data set. For the E-W wet mine site along road 700N this attenuation and delay is consistent with the substantial collapse encountered in the confirmational drill holes along this same eastern margin of the Bunsenville Mine a short distance to the south.

One facet of these data that appears to be a contradiction, but is not, is the relatively continuous amplitude of the second arrivals across the same traces that exhibit an attenuation of the first arrivals. A ray trace model (Figure 22) shows how the second arrivals refract from a shallower layer than that of the first arrivals. Consequently they miss the mined area and maintain relatively uniform amplitude across the spread. However, the refraction from the deeper layer that is associated with the first arrivals in these data, has some of its rays passing thorough the mined area and become attenuated as a result. If the recording spread had been longer the second arrivals would have been expected to also encounter the mine and similarly shown attenuation. A time delay of about 10 ms may also associated with the attenuated first arrival, especially in the wet mine data set (Figure 21). Such a time delay would be consistent with the significant degree of degradation and collapse of the rock directly above the Bunsenville Mine as encountered in the confirmational drill holes to the south.

Conclusions

The primary method of using the seismic energy generated by the mining operation to detect the margin of old mine workings was successful in the wet mine case. In addition, the direction and location of mining did not appear to make a significant difference for the generation of detectable scattered seismic energy that was converted at the old mine margin from the in-seam waves. The lack of a similar seismic signature detected from the mine margin in the dry mine case may indicate that in that location and/or setting the in-seam waves may have been reflected back along the coal seam without the conversion of significant seismic energy detectable at the surface, or at least not effectively scattered to the surface. Whether this difference for this very young air-filled mine may be due to the presence of air in the void (high impedance contrast), a potentially vertical planar boundary without roughness to scatter in-seam seismic energy, or the lack of collapse to increase the potential for conversion and scattering of seismic energy (in contrast to that of the wet-mine example studied which is 60 years old and experiencing significant collapse) is difficult to assess with the present data. Further study at the margin of older dry mines might confirm whether the present example reveals a potential limitation to our new method for detecting air-filled mines, or whether some a factor other than the mere presence of air in this example contributes to the lack of detected signal at the surface. In addition, the study of a wet-mine example that has not experienced the substantial collapse modification might help determine if the effects of collapse (rubble-filled mine void and roof rock modification) is an important factor in scattering the seismic energy traveling in or along the coal seam. Nevertheless, the fundamentally new seismic method demonstrated here was successful in detecting the wet mine margin using seismic energy generated by mining operations 1200 feet away from the old mine margin, to within about 90 feet laterally. Consequently, this new seismic method for locating old mines using the energy generated by active mining nearby has great promise, especially for old flooded mines. However, it should be cautioned that the method is still in development and should not be considered an off-the-shelf tool to be widely applied yet, without a better understanding of the abovementioned potential limitations.

An in-seam seismometer emplaced in the upper quarter of the coal seam recorded seismic waves associated with mining activity. These waves appear dominated by Rayleigh-type particle motion in a vertical, nearly E-W plane and prograde motion toward the west, away from the source of mining activity east of the seismometer. The dominant frequencies of these waves are about 15Hz and 22Hz, which is too high for the Airy phase in a coal seam of this thickness. Instead, it is inferred that these dominant frequencies and their high amplitude may be Rayleigh-type waves related to the periodic strong coupling of the cutter head of the continuous miner as it extracts coal rather than an consequence of dispersion.

The secondary method examined, that of using refraction energy returning from a level deeper than the coal seam to detect attenuation associated with mined areas, had limited success, but did appear to observe an associated effect on the relative amplitude of refraction wave arrivals passing through old mine works.

Future Directions and Questions

This initial study used a linear spread of surface geophones in order to demonstrate the method as a viable concept. However, a series of lines or an grid of sensors on the surface could be deployed to attempt to map the aerial pattern of the scattering from an irregular old mine margin. Such a follow-up study is a clear next step for demonstrating the potential broader practical application of this method.

Acknowledgements

We acknowledge the financial support of MSHA, Department of Labor, to Wright State University for this study. The study would not have been possible without the support and assistance of Black Beauty Coal Company, now part of Peabody Energy (in particular Phil Ames, Dick Reisinger, Eric Quom, and Charles Austin). Some of the seismic recording equipment was provided by the IRIS consortium (Incorporated Research Institutions for Seismology), of which Wright State University is a member. Magnum Drilling was accommodating in the scheduling of the drilling program. We also appreciate the cooperation of the landowners and tenant farmers who allowed access for this study.

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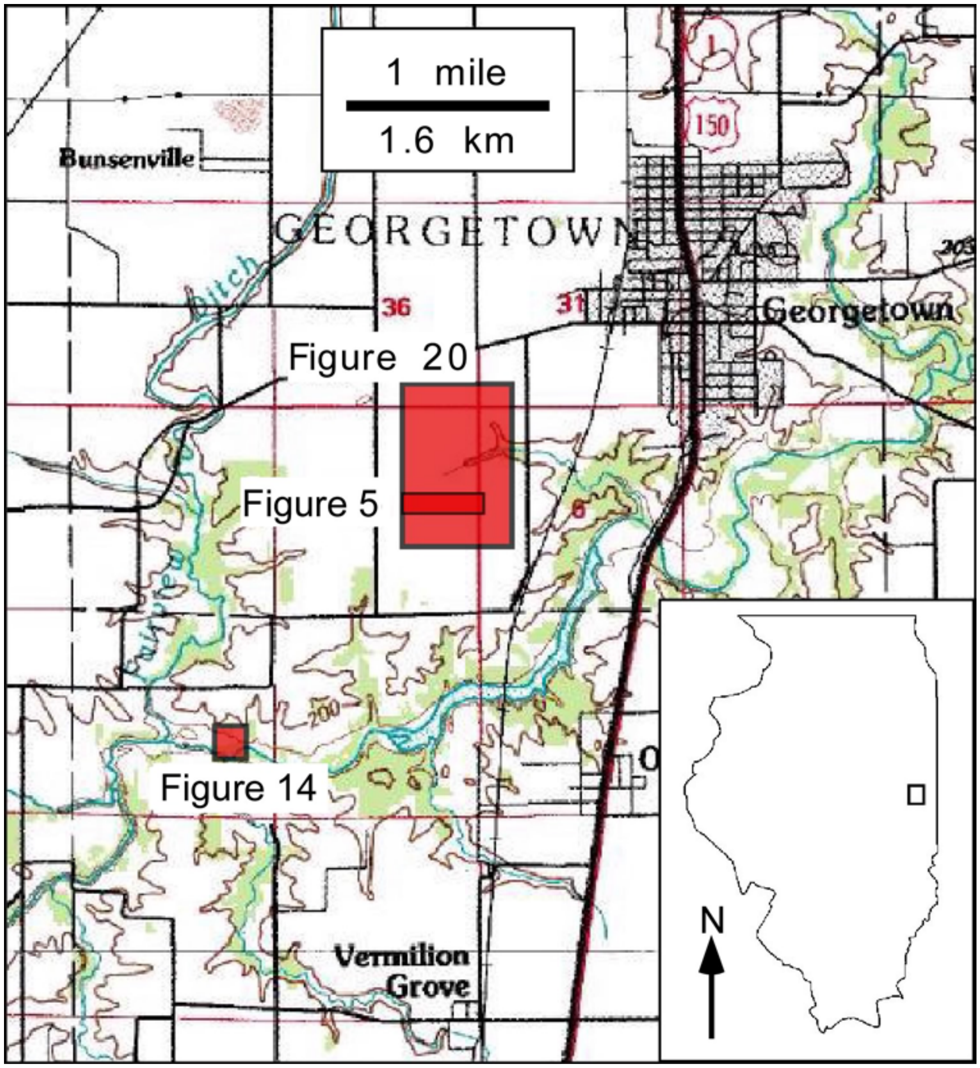


Figure 1. Location map of the primary study areas of this project near Georgetown, Illinois. Red boxes denote the location and area of other figures in this report.

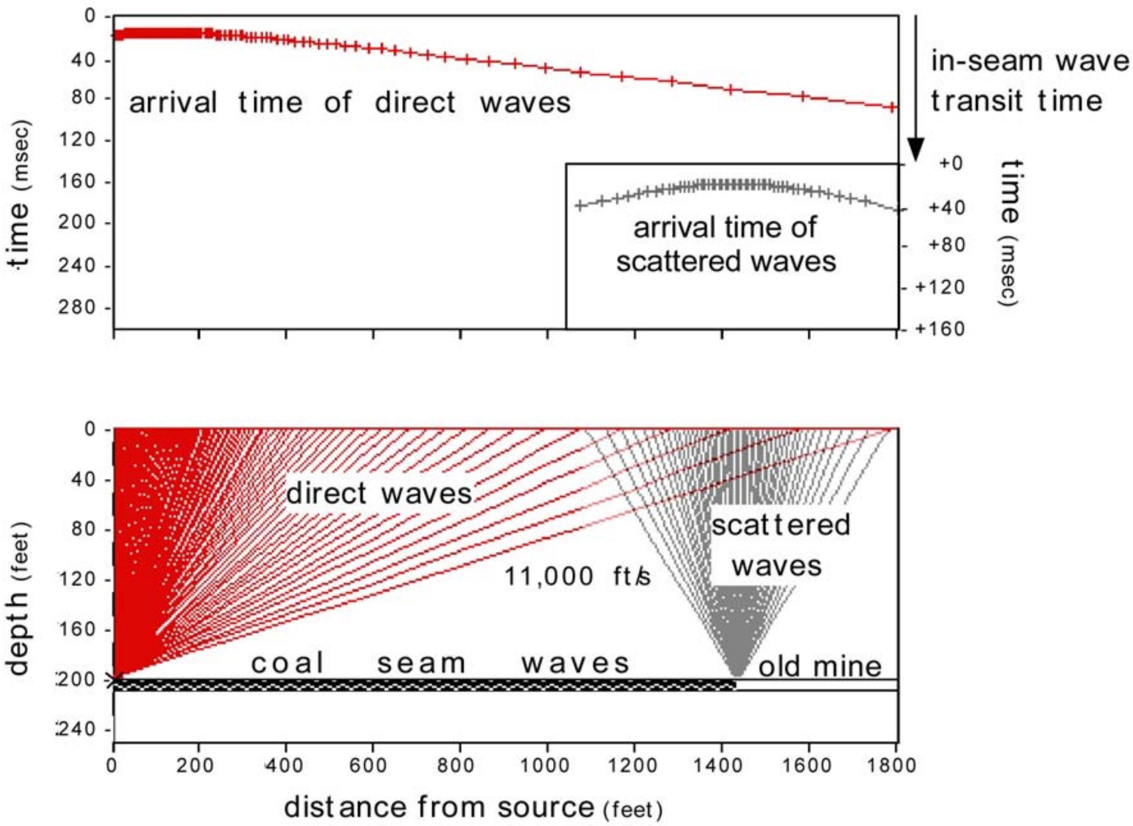


Figure 2. This generalized ray-trace model and associated travel time plot show the path and arrival of seismic energy for the new method described in this report. In this depth model the top of a 6 foot thick coal seam is placed at a depth of 200 feet, analogous to that at the study site. Red lines in the depth model are a series of rays traced from their source at the mining equipment in the coal seam and to the surface, taking a path defined by the range in seismic velocities defined in the depth model. In this simple model the rock velocity used is a constant 11,000 ft/s. In more complex models a range of velocities can be defined which cause the rays to refact or bend along their path. From the source point a series of rays is sent out at a range of angles, and propogated through the velocity model, with some eventually being successfully traced to the surface, as shown in this example. In the depth model shown here, the red rays denote the seismic energy traveling directly from the active miner in the coal seam to the surface through the overlying bedrock having a P-wave velocity of 11,000 ft/s. The red curve on the time section above shows the corresponding arrival time of seismic energy of a single impulse of seismic energy traveling along each of the many ray paths to the surface, all starting at the same time from the source. The gray rays fanning to the surface in the model are

calculated in a similar way as described above, but radiating from a ‘source’ at the mine margin, and denote the path of seismic energy that would be expected when the in-seam seismic energy is converted to P-wave energy. The gray curve in the sub-box in the time section shows the arrival time of these converted P-waves relative to the time the conversion occurred at the mine margin. The in-seam wave travel time is immaterial to the method, only the relative travel time of the wave train of the converted seismic energy from its point of origin at the old mine margin to the surface is pertinent.

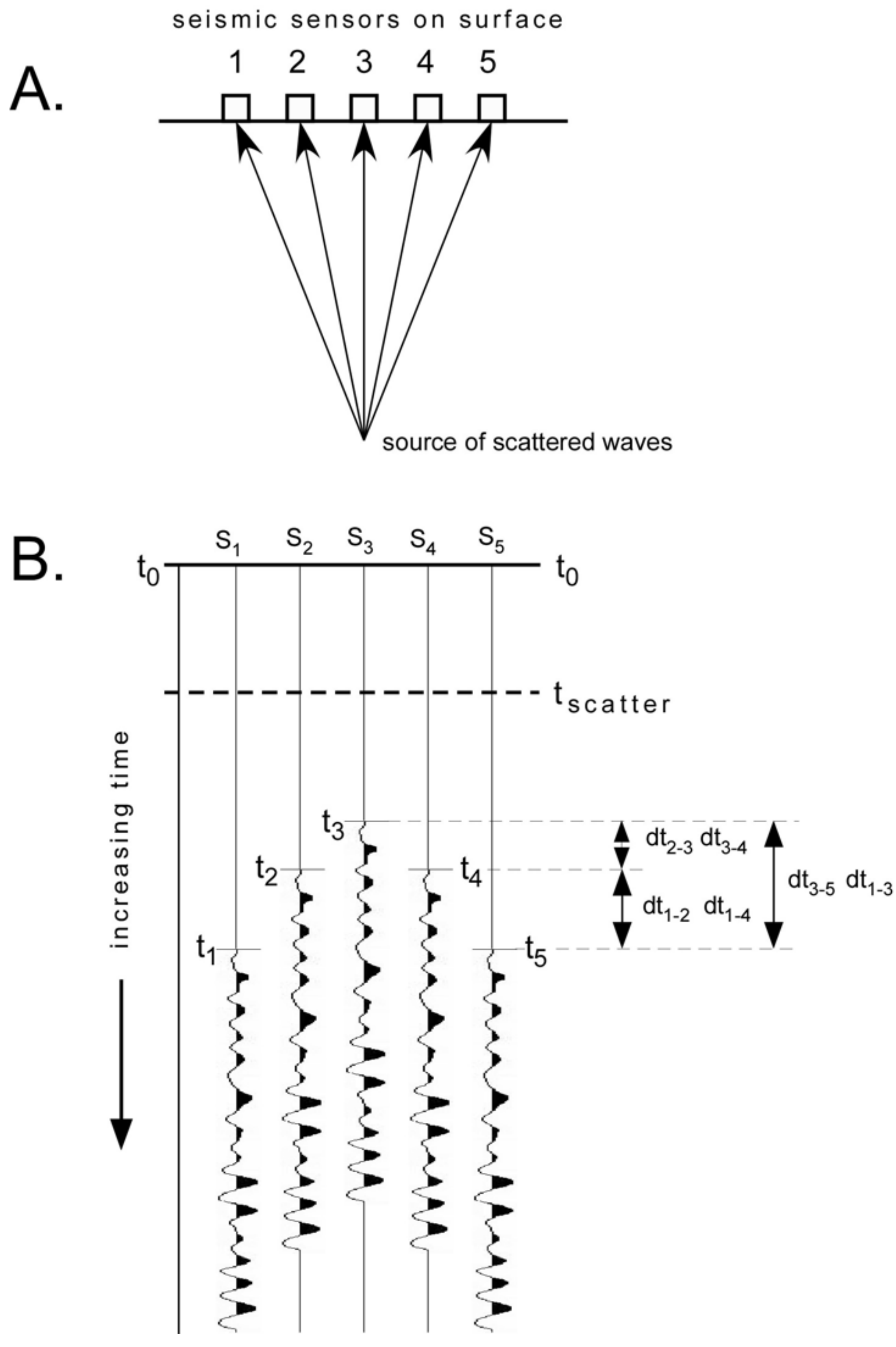
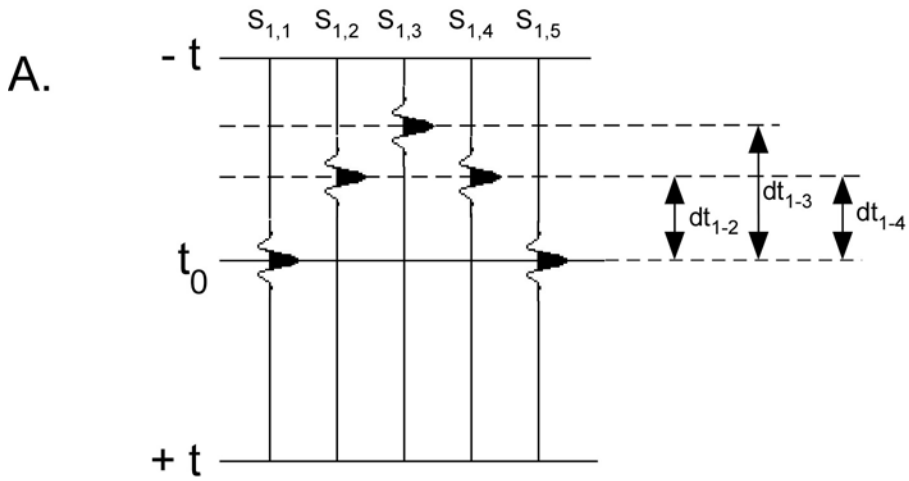


Figure 3. Description of how a seismic wave train that emanates from a subsurface point will show up in the seismic data recorded at a number of closely adjacent seismic sensors. The arbitrary beginning of the record is labeled t_0. (A) A diagrammatic cross section showing the ray path of seismic waves emanating from a subsurface location and arriving at seismic sensors at the surface. (B) A diagrammatic representation of the seismic wave forms recorded at the sensor locations represented in A and showing the wave train arriving with small relative time shifts at each location.



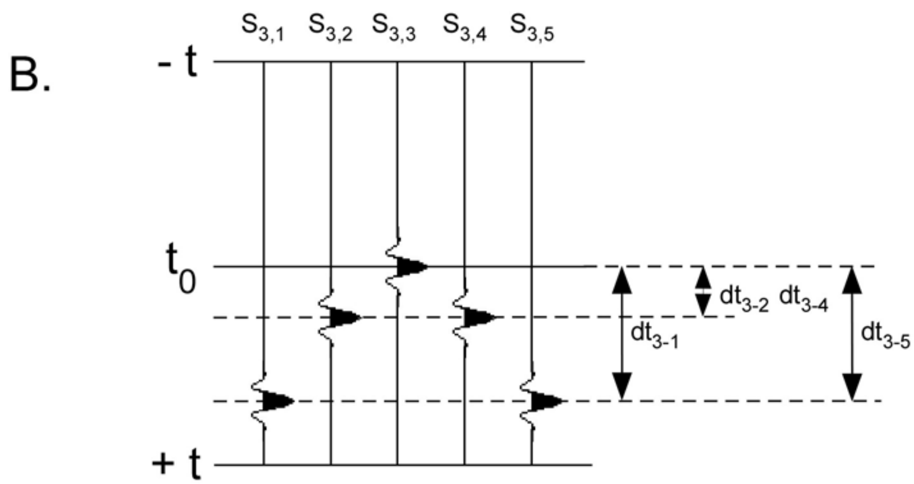


Figure 4. Examples of the result of crosscorrelation for the schematic data traces shown in Figure 3B. The correlation coefficient is a symmetrical zero phase wavelet. Relative times between the correlation wavelets among a collection of closely adjacent traces containing substantially the same, but shifted, wave train, remain the same despite which trace is used for correlation. The pattern shifts up and down depending upon which autocorrelation defines the t_0 of the correlated data. (A) Trace 1 is used for the crosscorrelation, making trace $S_{1,1}$ an autocorrelation which defines the t_0 of the resulting cross-correlated record. (B) Trace 3 is used for crosscorrelation, making trace $S_{3,3}$ an autocorrelation which defines the t_0 of the resulting cross-correlated record.

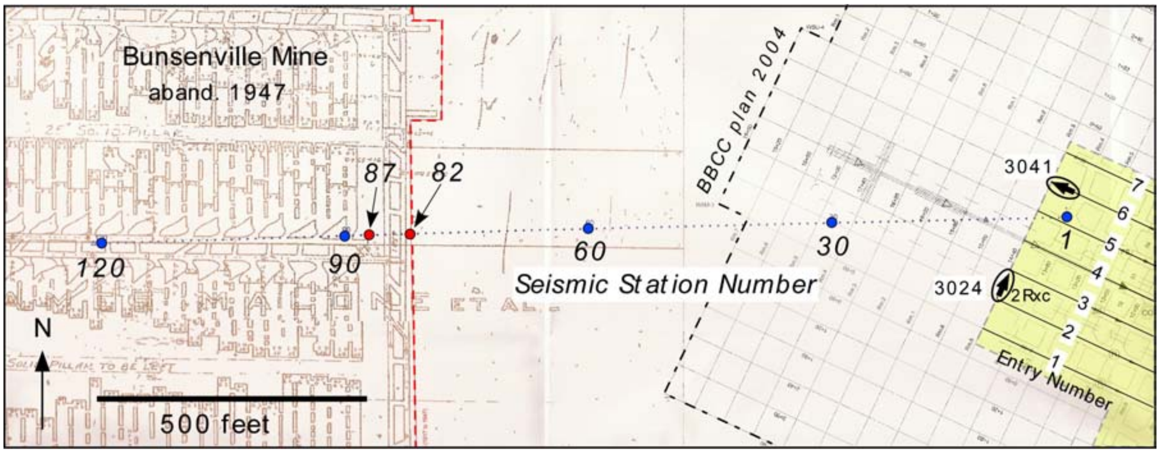


Figure 5. The detailed location of the surface seismic line across the margin of the flooded Bunsenville Mine is overlain on a base map provided by Black Beauty Coal Company. The base map shows their best estimate of the location of the old flooded Bunsenville Mine and the new area being mined at the time of the fieldwork for this project. Seismic stations are shown as faint blue dots with stations of particular significance identified with a larger blue or red dot and numbered. The locations of the directional data of Figure 13 are denoted with circled arrows that identify the direction of mining. The area labeled 'BBCC plan 2004' was subsequently mined but only the yellow-shaded area near Station 1 was mined at the time of the seismic data acquisition for this study.

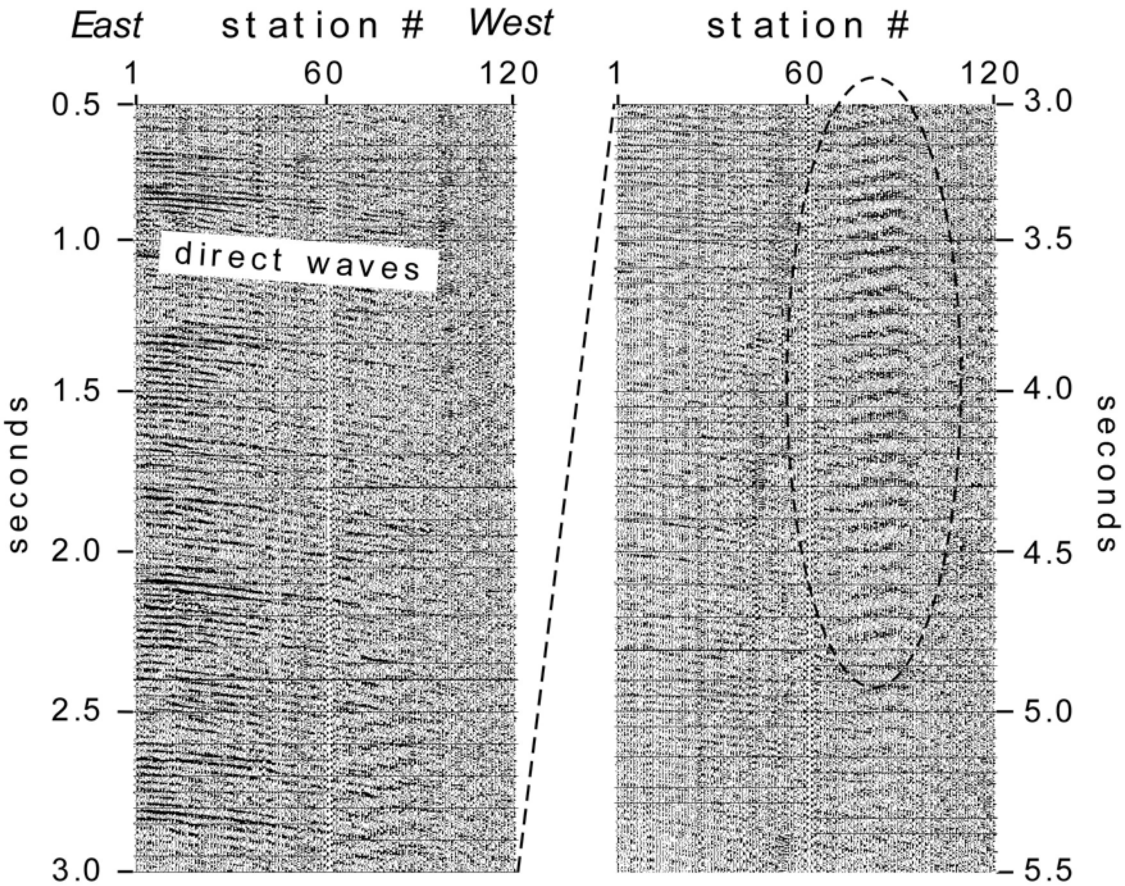


Figure 6. This 5-second portion of a raw field record shows the multitude of impulsive direct arrivals from the mining operation. Circled is the oscillatory signal that is seen on some raw data records at the location of the margin of the old mine works.

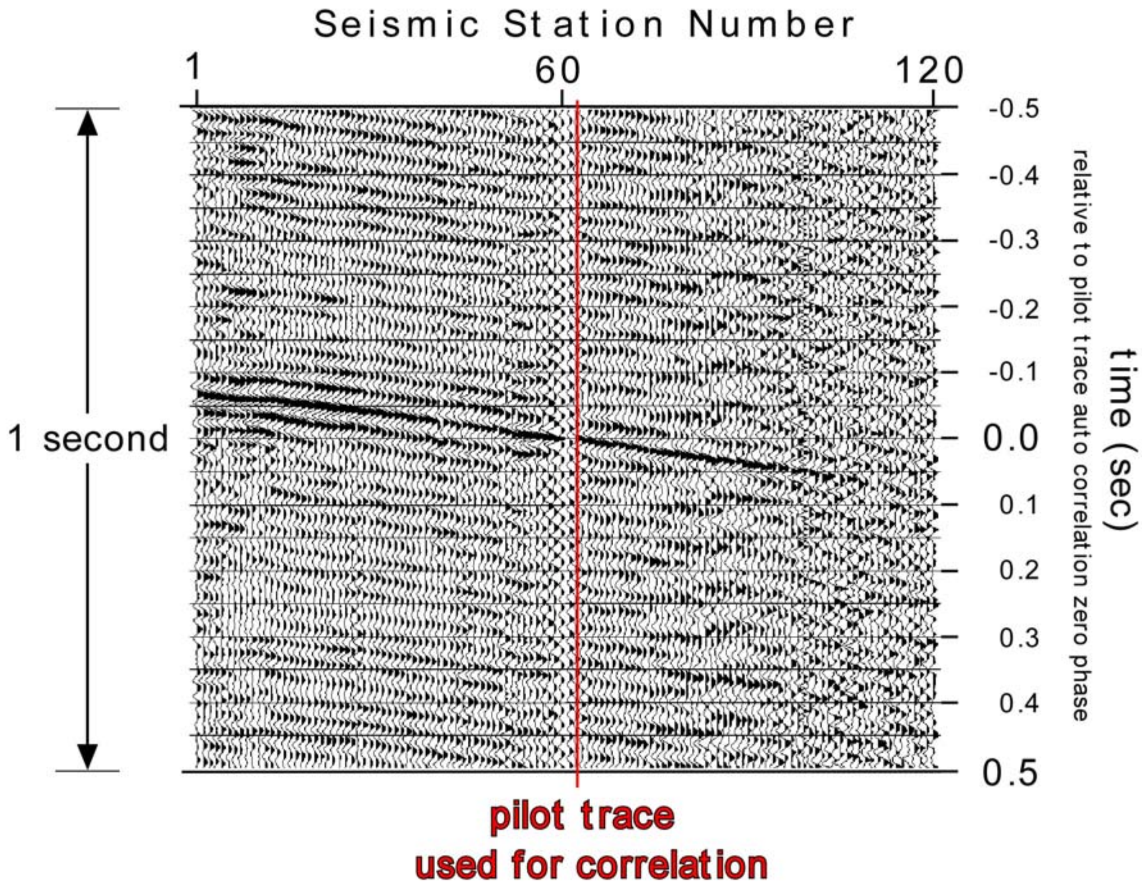


Figure 7. This is a data sample of a crosscorrelation using the trace at station 62 as the pilot sweep. Time is relative. with zero time defined as the zero-phase autocorrelation of the pilot sweep.

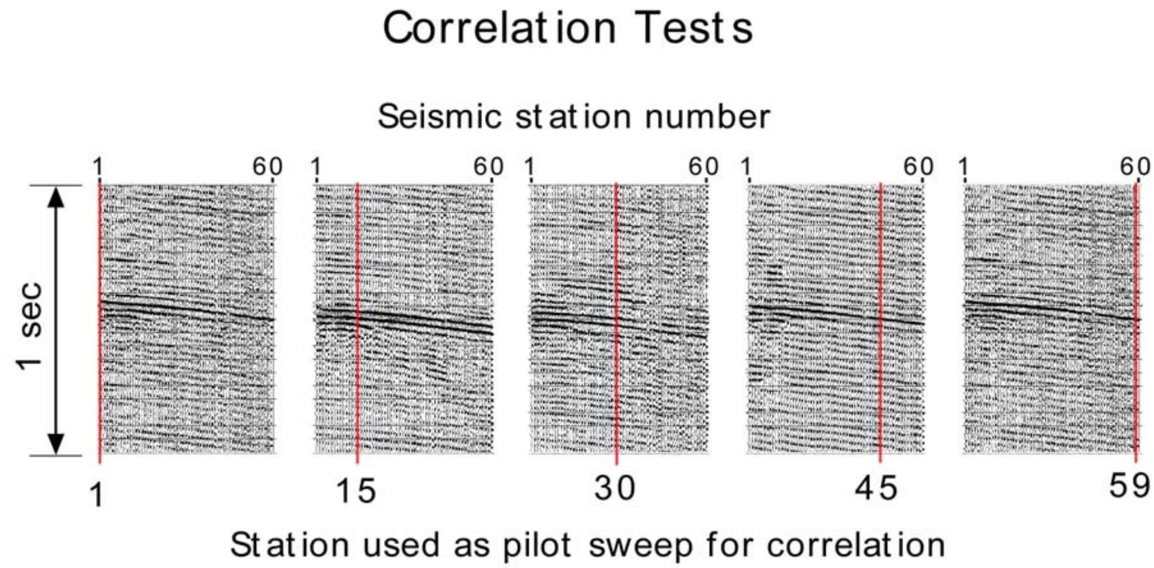


Figure 8. Examples of correlated data using different traces as the pilot trace for correlation (shown in red). The direct arrival is well developed regardless of the pilot trace used.

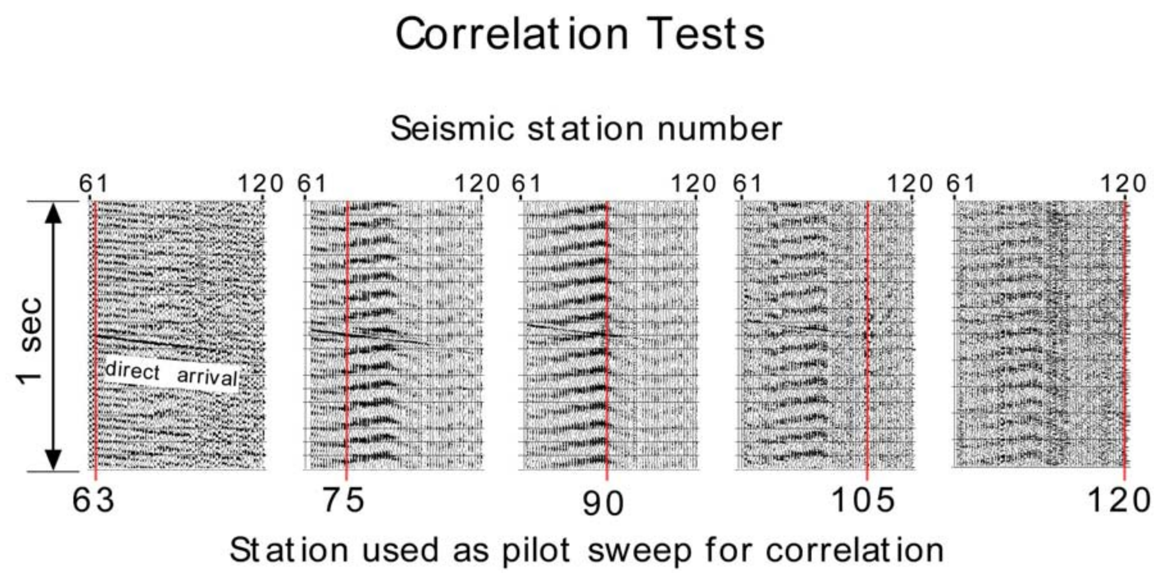


Figure 9. Examples of correlated data using various traces as the pilot trace for correlation (shown in red). The direct arrival is well developed almost regardless of the pilot trace used, although it weakens significantly at greater offset due to the critical angle of seismic energy at the coal/rock interface being approached and the increasingly emergent wave at the vertical geophone at greater offsets. The distinct concave downward oscillatory signal seen in some raw data (Figure 6) is well developed in most correlated records when using pilot traces in the 70-90 range, as seen above.

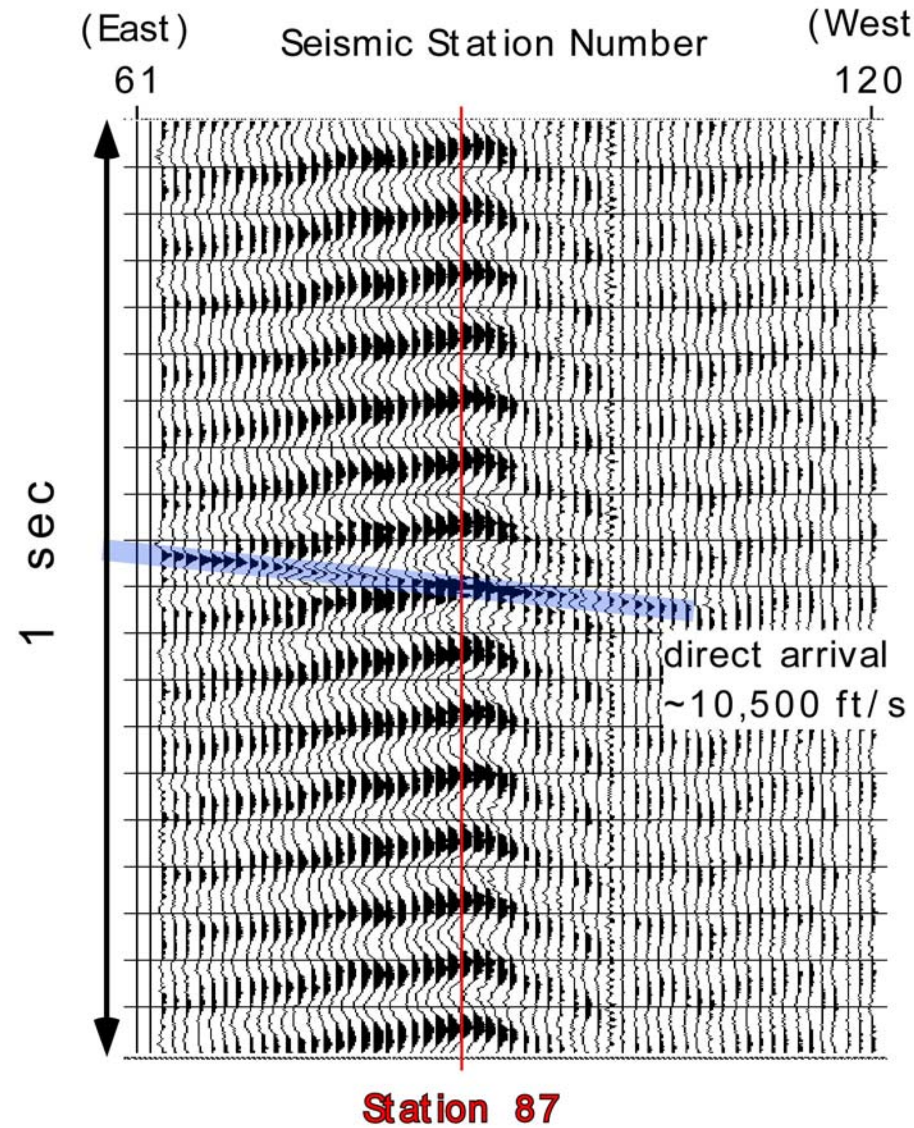


Figure 10. Enlargement of a correlated record showing both a well developed direct arrival and the prominent oscillatory signal spatially related to the margin of the flooded Bunsenville Mine. Seismic station 87 (highlighted in red) was used as the pilot sweep for the correlation. The direct P-wave arrival of about 10,500 ft/sec is highlighted in blue.

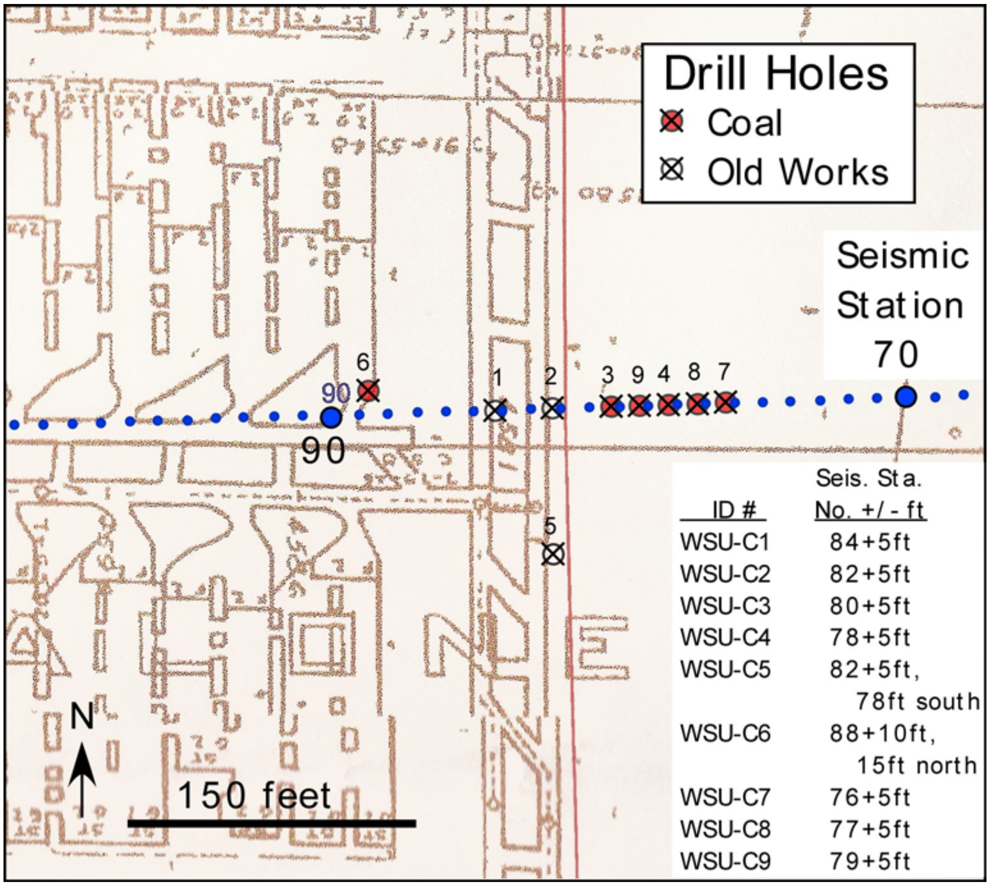


Figure 11. Detailed location map of the confirmational drill holes in relation to the seismic stations (blue dots) and the mine plan at margin of the flooded old Bunsenville Mine. Red drill-hole symbols denote intact coal was encountered, white drill-hole symbols indicate that old works were encountered (coal was absent). Drilling indicated that all of the old mine works had collapsed and water rose to within about 10 feet of the ground surface.

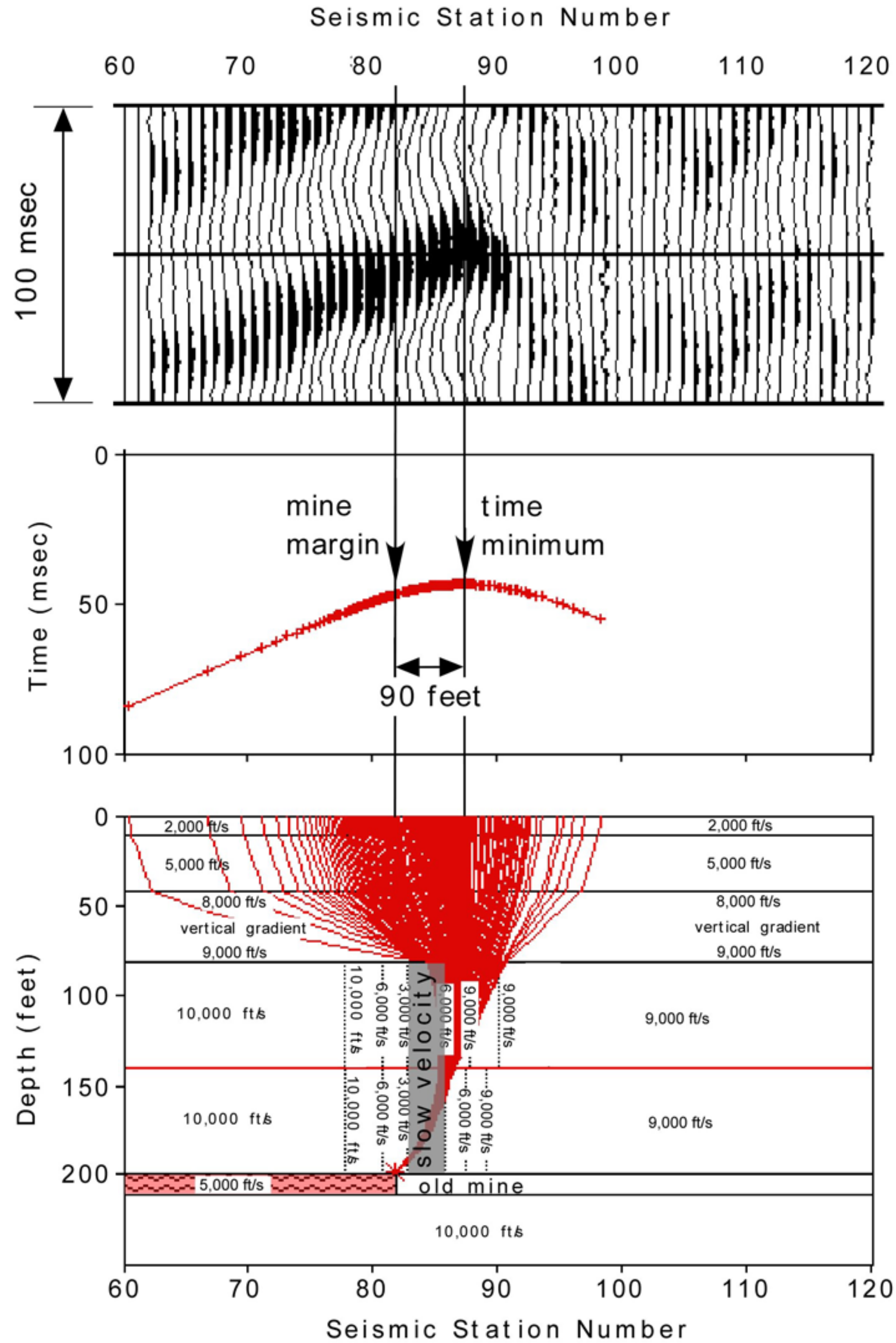


Figure 12. Speculative ray trace model constructed to demonstrate how a low velocity zone resulting from fracturing and collapse above the old flooded mine can explain the 90 foot lateral shift of the crest (minimum time) of the scattered wave signature in relation to the actual location of the flooded mine margin. Velocities were adjusted in the model to enable the fit of both the location of the minimum arrival time and the relative arrival times observed in our data and with the assumption that the seismic energy emanated from the location of the margin of the old mine as confirmed by drilling.

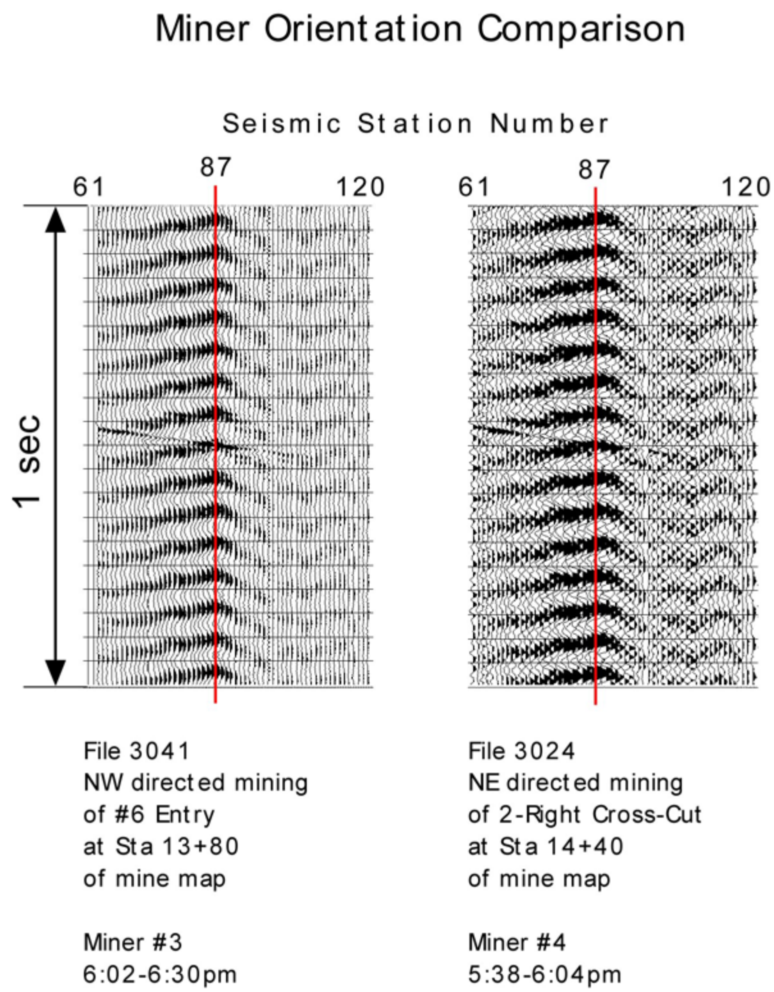


Figure 13. Comparison of correlated records representing a 90 degree difference in the direction of mining advance, as annotated above. See Figure 5 for locations.

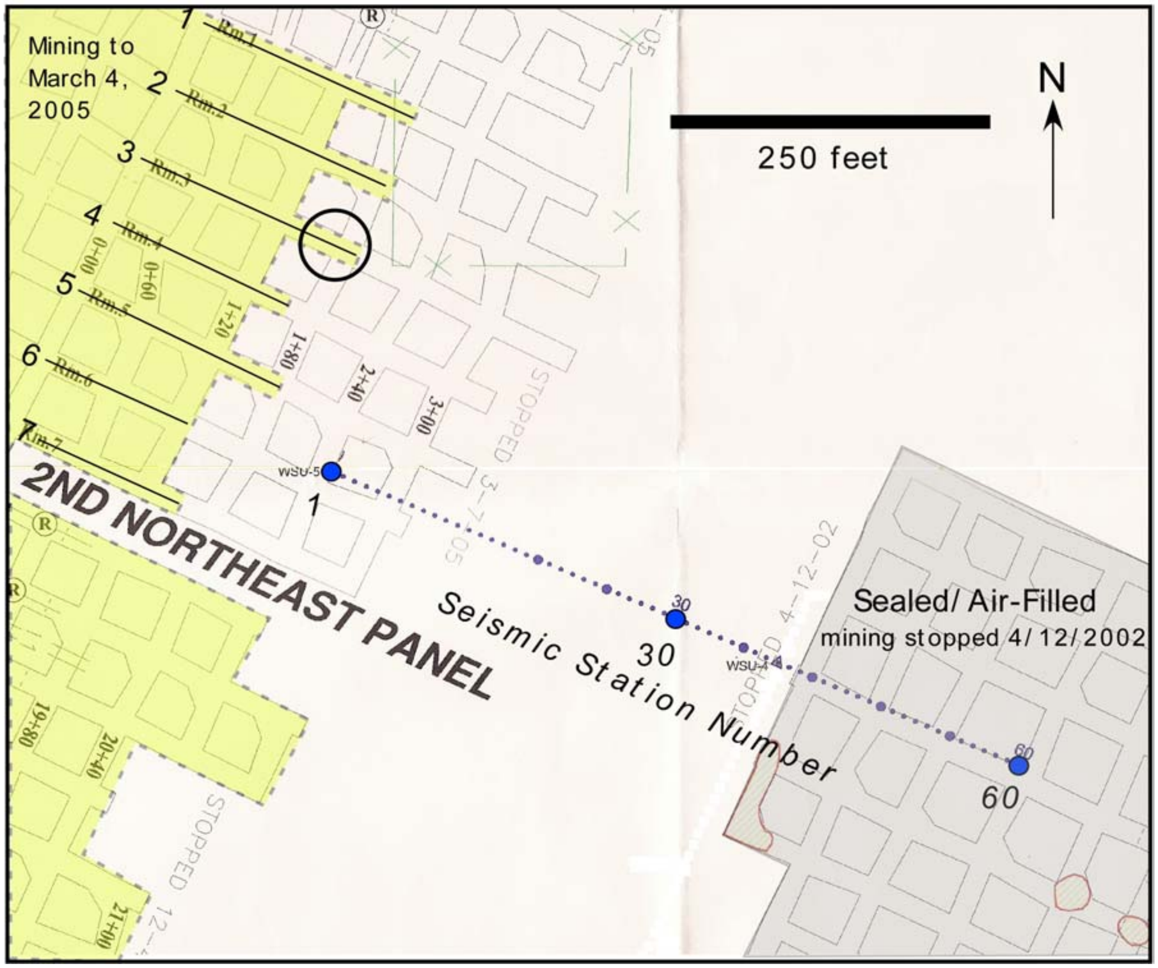


Figure 14. Location of the seismic stations (blue dots) at the dry mine site on a base map provided by Black Beauty Coal Company. See Figure 1 for the location of this map with respect to other areas studied. Gray-shaded area denotes a part of the current Vermillion Grove Mine abandoned and sealed 3 years previous. Yellow denotes the area mined at the time of field recordings across the margin of the abandoned mine at this location. Circled is the area being mined when the dry-void data set discussed herein was recorded.

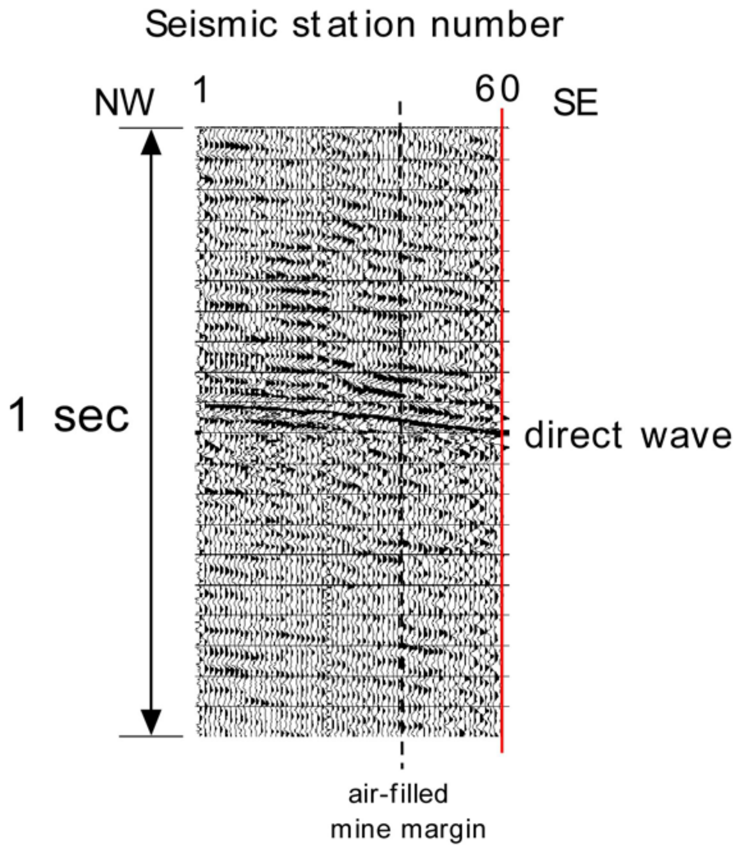


Figure 15. Correlated record of data across the air-filled mine margin exhibiting a clear direct arrival through the rock overlying the coal seam. A mine margin signal like that found at the water-filled mine site is absent here. This may suggest that the coal/air interface is a specular reflector resulting in the in-seam seismic waves being almost entirely reflected within the coal seam with little of it converting to seismic energy that reaches the surface.

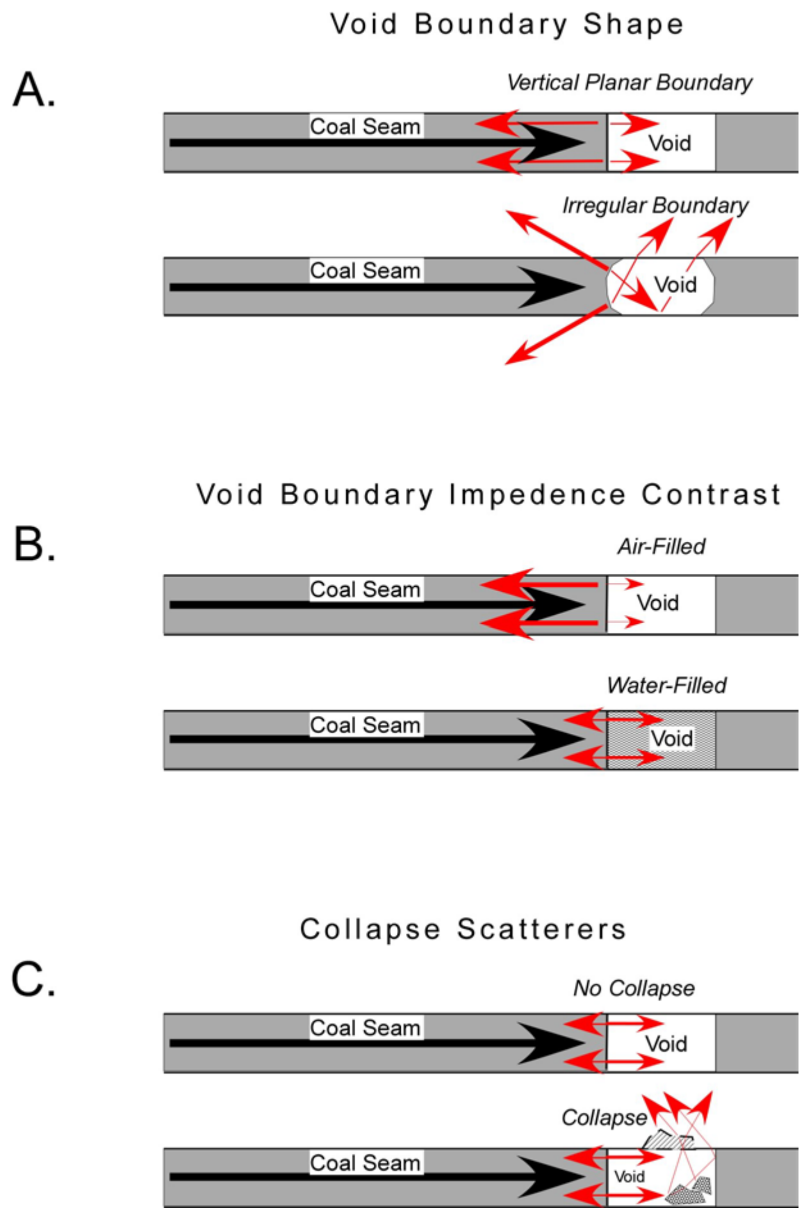


Figure 16. Schematic representation of some of the factors contributing to the scattering of seismic waves traveling in or along the coal seam when they encounter a mine void.

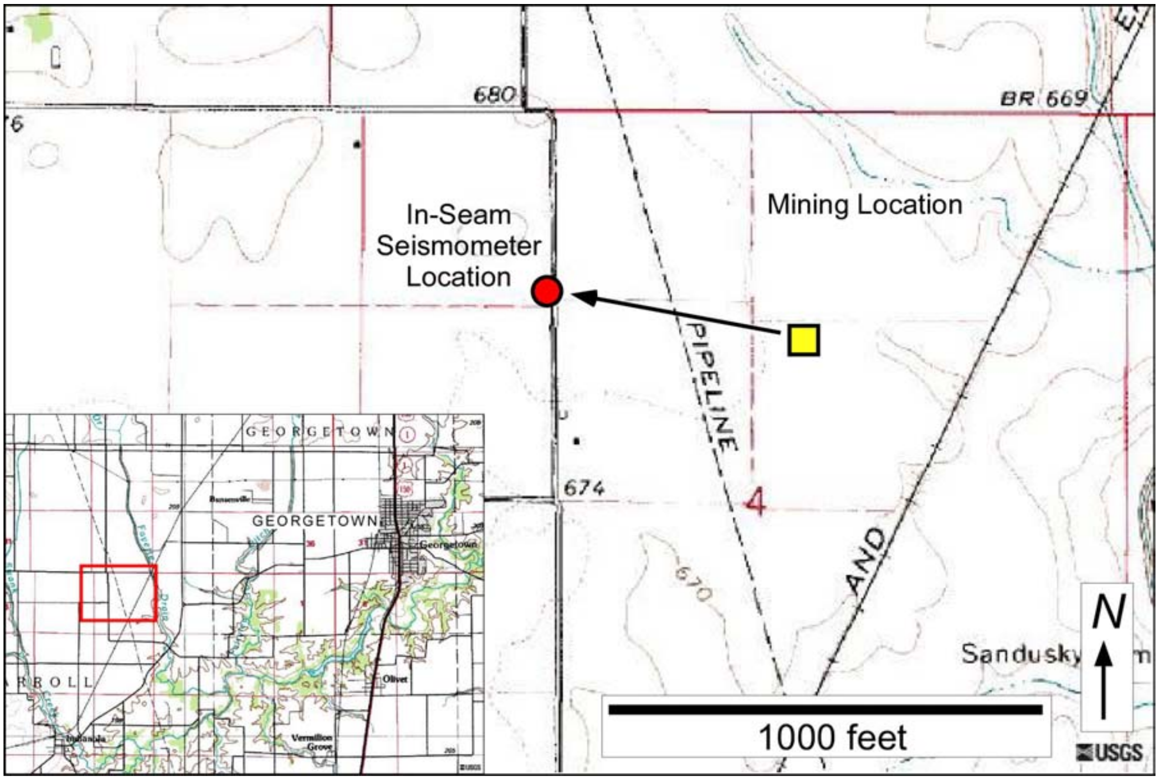


Figure 17. Location of the in-seam borehole seismometer (red-filled circle) in relation to that of the associated mining activity (yellow-filled square).

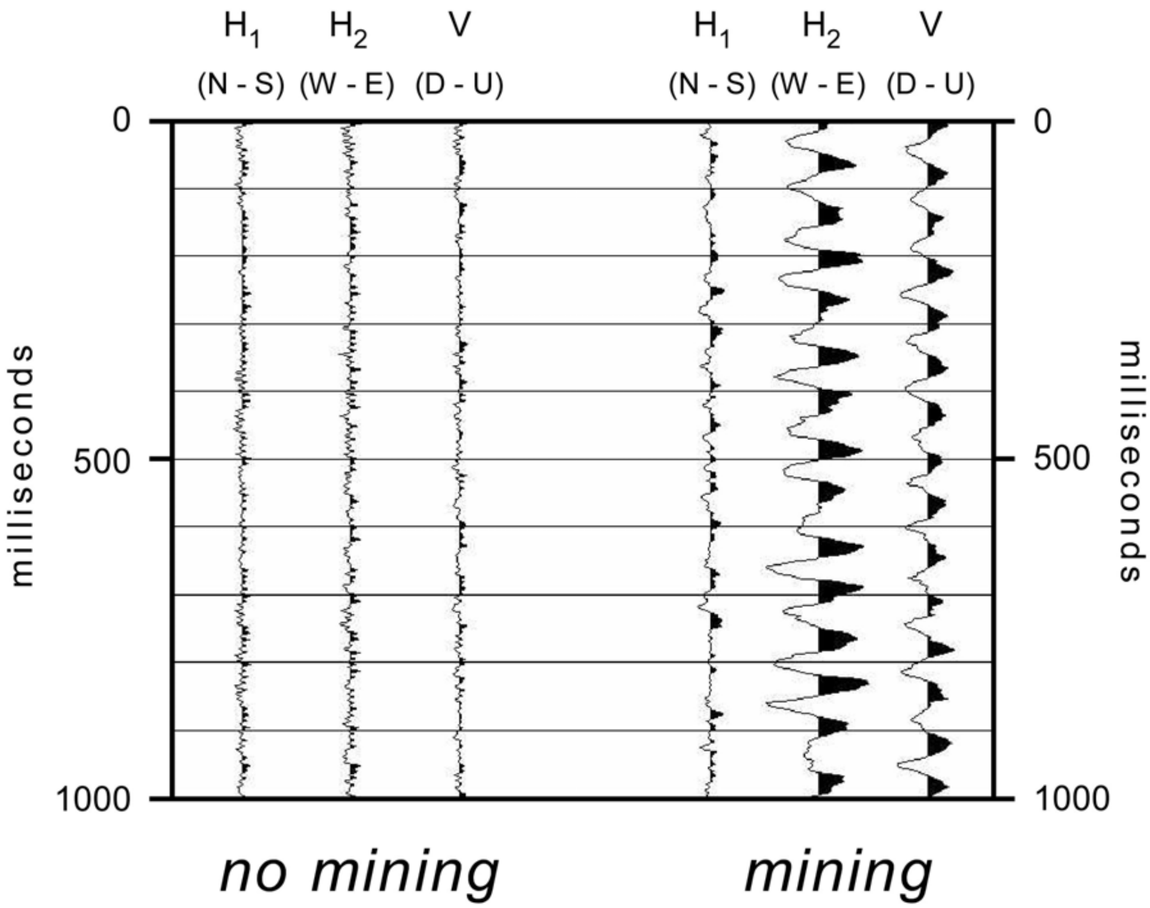


Figure 18. Data recorded by the 3-component in-seam seismometer both with and without active mining nearby. All traces are scaled to the same gain. The dominant signal evident in relation to mining activity is about 14 Hz and strong on the E-W H2 and vertical components. Minimal activity is evident on the N-S H1 component during this mining. Particle motion evident in the E-W vertical plane is circular top to the west.

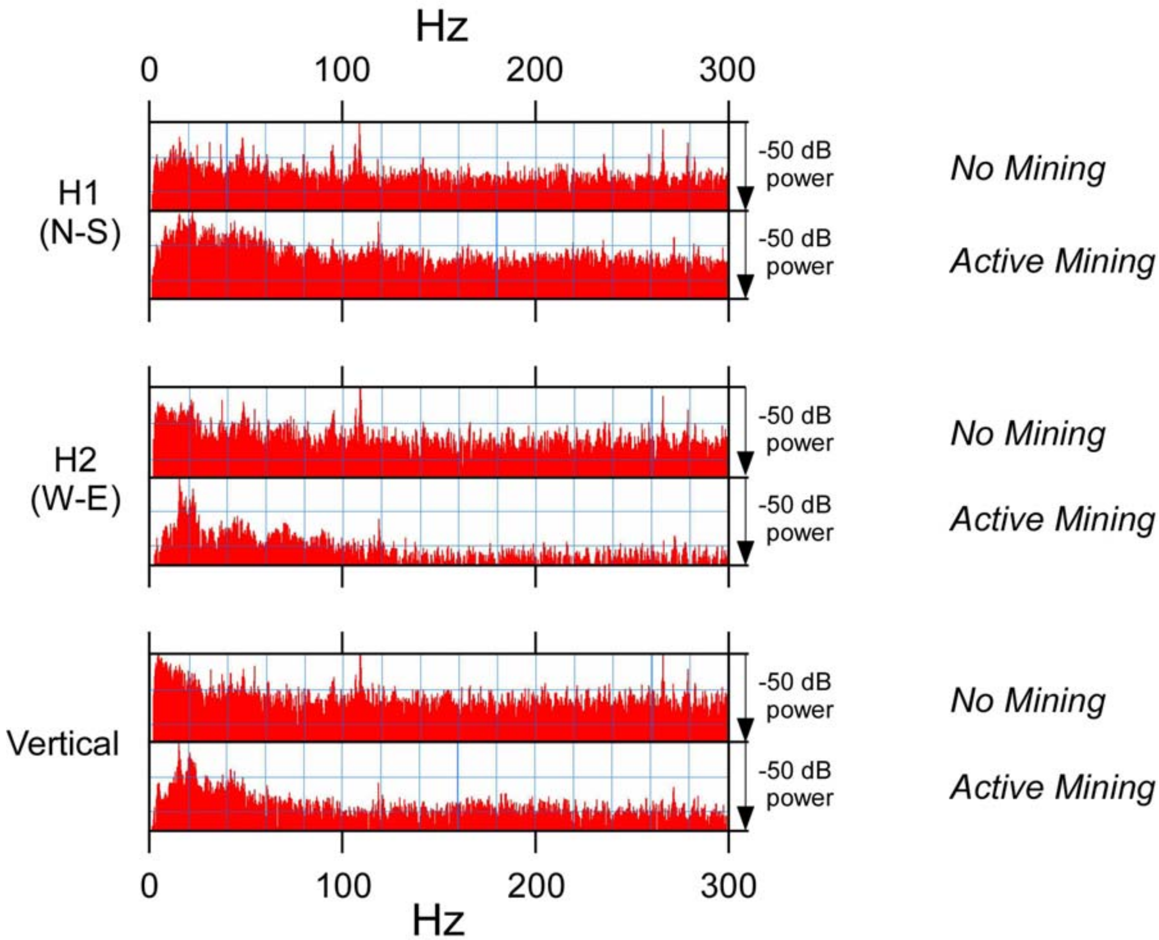


Figure 19. Comparison of frequency spectra for each seismometer component from a 4 second record, with and without mining activity present. The mining signal is strongest (45dB to 50dB above background) on the H2 (E-W) and the Vertical components with the strongest signal at 15Hz and 22Hz.

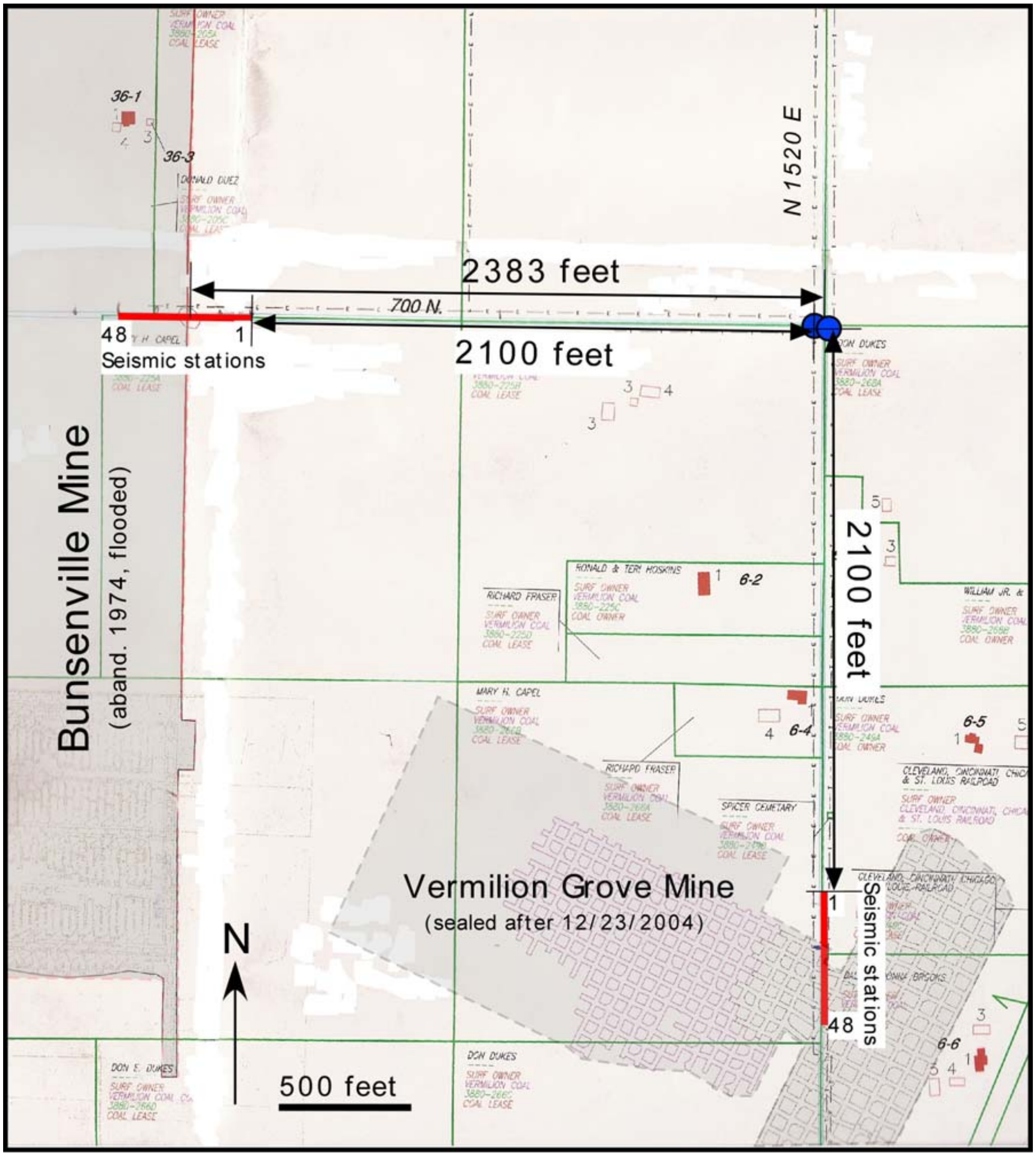


Figure 20. Location map of refraction wave attenuation observations of the secondary method of this project. Red lines represent the locations of seismic spread of geophones on the surface, one across the margin of the flooded Bunsenville Mine, one across recently abandoned parts of the Vermilion Grove Mine. Gray shaded areas are mined.

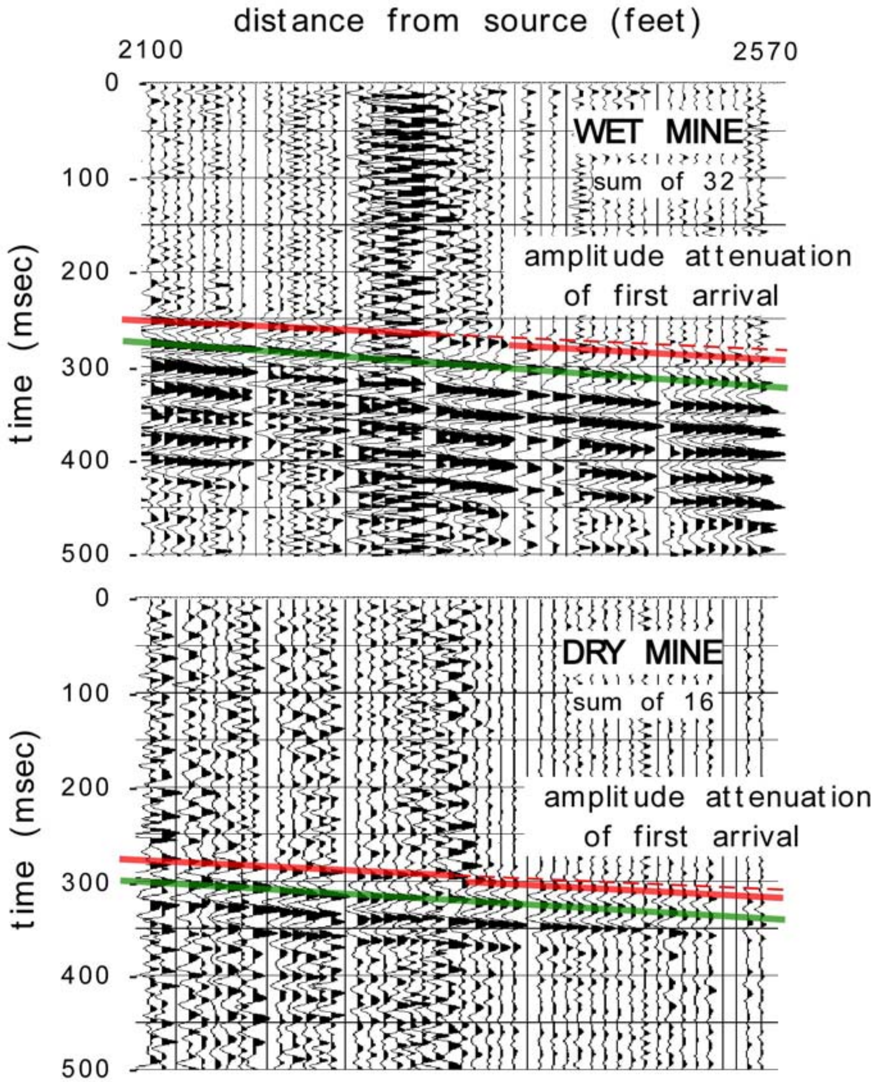


Figure 21. Refraction arrivals from a weight-drop source at a location 2100 feet from station 1 for both data sets. A solid red line traces the first refraction arrival, which appears to exhibit a decrease in amplitude across both mine margins. A solid green line traces a second arrival of refraction energy that does not appear to exhibit an amplitude change. A red dashed line is the projection of the solid red line and suggests a time shift may be associated with the refraction wave attenuation. Red and green correspond to the rays of the same color modeled in Figure 22.

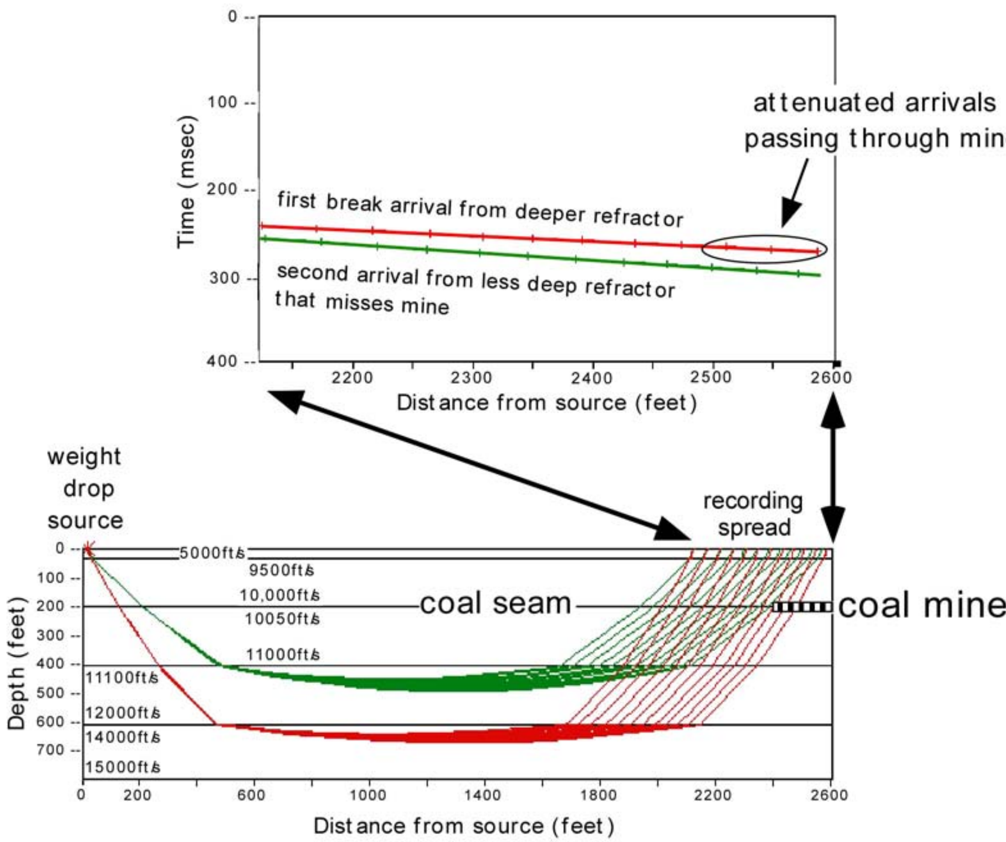
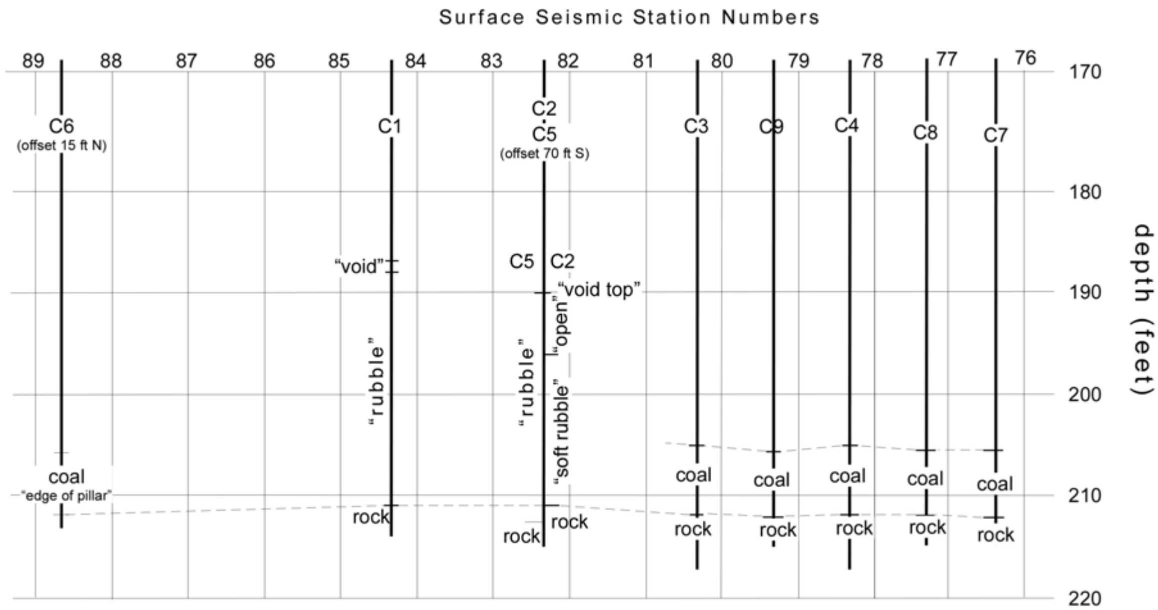


Figure 22. A schematic ray trace model shows how seismic waves refracted along various rock layers at depth arrive at the surface recording spread deployed across the mine margin. Depending on the depth and relative velocities, some refracted seismic waves (green) may miss the mine while some deeper refracted seismic waves (red) may pass through and become attenuated by the mined area.

Appendix 1. Driller Logs for Confirmational Drill Holes at Wet Void Site



Summary of confirmational bore hole information from the drillers logs of this Appendix and from notes taken in the field during the drilling.

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC1
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	CORE Cut	CORE Rec.	DRILLING FEET FROM	TO	Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	29.00	3.00	058.3		UNCONS sand w/gravel med gray		
			29.00	33.00	4.00	057.3		UNCONS silt w/gravel med gray - SANDY		
			33.00	39.00	6.00	058.3		UNCONS sand w/gravel med gray		
			39.00	110.00	71.00	334		SANDY SHALE med gray		
			110.00	114.80	4.80	020		**COAL**		
			114.80	118.00	3.20	131		CLAYSTONE med gray		
			118.00	128.00	10.00	331		SANDY CLAYSTONE med gray		
			128.00	131.00	3.00	338		SANDY SHALE med gray w/siderite nodules		
			131.00	137.00	6.00	334		SANDY SHALE med gray		
			137.00	140.00	3.00	530		SANDSTONE med gray		
			140.00	146.00	6.00	333		SANDY SHALE med gray w/sandstone strks - LIME NODULES		
			146.00	169.00	23.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			169.00	182.00	13.00	530		SANDSTONE med gray		
			182.00	187.00	5.00	334		SANDY SHALE med gray		
			187.00	188.00	1.00	005		OLD WORKS-voids - OPEN		
			188.00	211.00	23.00	005		OLD WORKS-voids - RUBBLE SOLID		
			211.00	214.00	3.00	331		SANDY CLAYSTONE med gray		
				214.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA			
DATE DRILLED		02-27-2006	
DATE COMPLETED		02-28-2006	
DRILLER	DANNY L	HELPER	BRETT
SURFACE ELEVATION			
TOTAL DEPTH		214.00'	
CORE SIZE			
CASING DEPTH		40.00'	
NUMBER OF CEMENT BAGS		1 YARD	

LOCATION

SECTION : TWNSHP : RANGE : QUAD :
COUNTY : VERMILION
STATE : IL

LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : WSUC1
SECTION HOLE# LEASE

NOTE: 30 FEET PVC CEMENT PLUG

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC2
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	CORE Cut	CORE Rec.	DRILLING FEET FROM	TO	Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	29.00	3.00	058.3		UNCONS sand w/gravel med gray		
			29.00	33.00	4.00	057.3		UNCONS silt w/gravel med gray - SANDY		
			33.00	39.00	6.00	058.3		UNCONS sand w/gravel med gray		
			39.00	111.00	72.00	334		SANDY SHALE med gray		
			111.00	114.60	3.60	020		**COAL**		
			114.60	118.00	3.40	131		CLAYSTONE med gray		
			118.00	128.00	10.00	331		SANDY CLAYSTONE med gray		
			128.00	131.00	3.00	338		SANDY SHALE med gray w/siderite nodules		
			131.00	136.00	5.00	334		SANDY SHALE med gray		
			136.00	141.00	5.00	530		SANDSTONE med gray		
			141.00	170.00	29.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			170.00	173.00	3.00	334		SANDY SHALE med gray		
			173.00	182.00	9.00	530		SANDSTONE med gray		
			182.00	190.00	8.00	334		SANDY SHALE med gray		
			190.00	195.00	5.00	005		OLD WORKS-voids - OPEN		
			195.00	211.50	16.50	005		OLD WORKS-voids - SOFT RUBBLE		
			211.50	215.00	3.50	331		SANDY CLAYSTONE med gray		
				215.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA			
DATE DRILLED		02-28-2006	
DATE COMPLETED		02-28-2006	
DRILLER	MICHAEL	HELPER	BRETT
SURFACE ELEVATION			
TOTAL DEPTH		215.00'	
CORE SIZE			
CASING DEPTH		40.00'	
NUMBER OF CEMENT BAGS		1 YARD	

LOCATION

SECTION : TWNSHP : RANGE : QUAD :
COUNTY : VERMILION
STATE : IL

LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : WSUC2
SECTION HOLE# LEASE

NOTE: 27 FEET PVC CEMENT PLUG

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC3
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	Cut	Rec.	FROM	TO	Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	29.00	3.00	058.3		UNCONS sand w/gravel med gray		
			29.00	36.00	7.00	057.3		UNCONS silt w/gravel med gray - SANDY		
			36.00	40.00	4.00	058.3		UNCONS sand w/gravel med gray		
			40.00	111.50	71.50	334		SANDY SHALE med gray		
			111.50	115.30	3.80	020		**COAL**		
			115.30	119.00	3.70	131		CLAYSTONE med gray		
			119.00	128.00	9.00	331		SANDY CLAYSTONE med gray		
			128.00	138.00	10.00	338		SANDY SHALE med gray w/siderite nodules		
			138.00	159.00	21.00	333		SANDY SHALE med gray w/sandstone strks - LIME NODULES		
			159.00	172.00	13.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			172.00	180.00	8.00	530		SANDSTONE med gray		
			180.00	205.00	25.00	334		SANDY SHALE med gray		
			205.00	212.00	7.00	020		**COAL**		
			212.00	215.00	3.00	331		SANDY CLAYSTONE med gray		
				215.00		D		START DRILLING - FOR CLEAN OUT		
			215.00	216.00	1.00	331		SANDY CLAYSTONE med gray		
			216.00	224.00	8.00	431		LIMEY SANDY CLAYSTONE med gray		
			224.00	226.00	2.00	020		**COAL**		
			226.00	227.00	1.00	131		CLAYSTONE med gray		
				227.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA

DATE DRILLED	02-28-2006	
DATE COMPLETED	02-28-2006	
DRILLER MICHAEL	HELPER	BRETT
SURFACE ELEVATION		
TOTAL DEPTH	227.00'	
CORE SIZE		
CASING DEPTH	41.00'	
NUMBER OF CEMENT BAGS	20	

LOCATION

SECTION : TWNSHP : RANGE : QUAD :
COUNTY : VERMILION
STATE : IL

LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : WSUC3
SECTION HOLE# LEASE

NOTE: 30 FEET 4 INCH PVC PIPE, CAP, 2 COUPLINGS

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC4
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	CORE Cut	CORE Rec.	DRILLING FEET FROM	DRILLING FEET TO	DRILLING FEET Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	41.00	15.00	058.3		UNCONS sand w/gravel med gray		
			41.00	111.50	70.50	334		SANDY SHALE med gray		
			111.50	115.30	3.80	020		**COAL**		
			115.30	120.00	4.70	331		SANDY CLAYSTONE med gray		
			120.00	128.00	8.00	338		SANDY SHALE med gray w/siderite nodules		
			128.00	159.00	31.00	333		SANDY SHALE med gray w/sandstone strks - LIME NODULES		
			159.00	172.00	13.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			172.00	183.00	11.00	530		SANDSTONE med gray		
			183.00	205.50	22.50	334		SANDY SHALE med gray		
			205.50	212.50	7.00	020		**COAL**		
			212.50	216.00	3.50	331		SANDY CLAYSTONE med gray		
			216.00	218.00	2.00	431		LIMEY SANDY CLAYSTONE med gray		
				218.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA			
DATE DRILLED		03-01-2006	
DATE COMPLETED		03-01-2006	
DRILLER	MICHAEL	HELPER	BRETT
SURFACE ELEVATION			
TOTAL DEPTH		218.00'	
CORE SIZE			
CASING DEPTH		42.00'	
NUMBER OF CEMENT BAGS		20	

LOCATION

SECTION : ____ TWNSHP : ____ RANGE : ____ QUAD : ____
COUNTY : VERMILION
STATE : IL
LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : ____ WSUC4 ____
SECTION HOLE# LEASE

NOTE: 30 FEET 4 INCH PVC PIPE, CAP, 2 COUPLINGS

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC5
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	CORE Cut	CORE Rec.	DRILLING FEET FROM	TO	Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	29.00	3.00	058.3		UNCONS sand w/gravel med gray		
			29.00	33.00	4.00	057.3		UNCONS silt w/gravel med gray - SANDY		
			33.00	43.00	10.00	058.3		UNCONS sand w/gravel med gray		
			43.00	112.00	69.00	334		SANDY SHALE med gray		
			112.00	115.90	3.90	020		**COAL**		
			115.90	120.00	4.10	131		CLAYSTONE med gray		
			120.00	128.00	8.00	331		SANDY CLAYSTONE med gray		
			128.00	134.00	6.00	338		SANDY SHALE med gray w/siderite nodules		
			134.00	136.00	2.00	334		SANDY SHALE med gray		
			136.00	141.00	5.00	530		SANDSTONE med gray		
			141.00	170.00	29.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			170.00	173.00	3.00	334		SANDY SHALE med gray		
			173.00	183.00	10.00	530		SANDSTONE med gray		
			183.00	190.00	7.00	334		SANDY SHALE med gray		
			190.00	213.00	23.00	006		OLD WORKS-Collapse - RUBBLE		
			213.00	219.00	6.00	331		SANDY CLAYSTONE med gray		
				219.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA

DATE DRILLED		03-01-2006	
DATE COMPLETED		03-01-2006	
DRILLER	MICHAEL	HELPER	BRETT
SURFACE ELEVATION			
TOTAL DEPTH		219.00'	
CORE SIZE			
CASING DEPTH		44.00'	
NUMBER OF CEMENT BAGS		1 YARD	

LOCATION

SECTION : TWNSHP : RANGE : QUAD :
COUNTY : VERMILION
STATE : IL
LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : WSUC5 (SECTION / HOLE# / LEASE)

NOTE: 32 FEET PVC CEMENT PLUG

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC6
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	CORE Cut	CORE Rec.	FEET FROM	TO	Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	29.00	3.00	058.3		UNCONS sand w/gravel med gray		
			29.00	33.00	4.00	057.3		UNCONS silt w/gravel med gray - SANDY		
			33.00	40.00	7.00	058.3		UNCONS sand w/gravel med gray		
			40.00	110.00	70.00	334		SANDY SHALE med gray		
			110.00	114.20	4.20	020		**COAL**		
			114.20	118.00	3.80	131		CLAYSTONE med gray		
			118.00	128.00	10.00	331		SANDY CLAYSTONE med gray		
			128.00	131.00	3.00	338		SANDY SHALE med gray w/siderite nodules		
			131.00	137.00	6.00	334		SANDY SHALE med gray		
			137.00	140.00	3.00	530		SANDSTONE med gray		
			140.00	146.00	6.00	333		SANDY SHALE med gray w/sandstone strks - LIME NODULES		
			146.00	169.00	23.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			169.00	182.00	13.00	530		SANDSTONE med gray		
			182.00	206.00	24.00	334		SANDY SHALE med gray		
			206.00	212.00	6.00	020		**COAL** - EDGE OF PILLAR		
			212.00	215.00	3.00	331		SANDY CLAYSTONE med gray		
			215.00	220.00	5.00	431		LIMEY SANDY CLAYSTONE med gray		
				220.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water : ____

DRILL HOLE DATA			
DATE DRILLED		03-02-2006	
DATE COMPLETED		03-02-2006	
DRILLER	MICHAEL	HELPER	BRETT
SURFACE ELEVATION			
TOTAL DEPTH		220.00'	
CORE SIZE			
CASING DEPTH		44.00'	
NUMBER OF CEMENT BAGS		1 YARD	
NOTE:	20 FEET PVC CEMENT PLUG		

LOCATION

SECTION : ____ TWNSHP : ____ RANGE : ____ QUAD : ____
COUNTY : VERMILION
STATE : IL
LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : ____ WSUC6 ____
SECTION HOLE# LEASE

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC7
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	CORE Cut	CORE Rec.	FROM	TO	Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	41.00	15.00	058.3		UNCONS sand w/gravel med gray		
			41.00	111.50	70.50	334		SANDY SHALE med gray		
			111.50	115.20	3.70	020		**COAL**		
			115.20	120.00	4.80	331		SANDY CLAYSTONE med gray		
			120.00	128.00	8.00	334		SANDY SHALE med gray		
			128.00	159.00	31.00	333		SANDY SHALE med gray w/sandstone strks - LIME NODULES		
			159.00	172.00	13.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			172.00	183.00	11.00	530		SANDSTONE med gray		
			183.00	206.50	23.50	334		SANDY SHALE med gray		
			206.50	213.20	6.70	020		**COAL**		
			213.20	216.00	2.80	331		SANDY CLAYSTONE med gray		
			216.00	220.00	4.00	431		LIMEY SANDY CLAYSTONE med gray		
				220.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA

DATE DRILLED	03-03-2006
DATE COMPLETED	03-03-2006
DRILLER MICHAEL	HELPER BRETT
SURFACE ELEVATION	
TOTAL DEPTH	220.00'
CORE SIZE	
CASING DEPTH	44.00'
NUMBER OF CEMENT BAGS	20

LOCATION

SECTION : TWNSHP : RANGE : QUAD :
COUNTY : VERMILION
STATE : IL
LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : WSUC7
SECTION HOLE# LEASE

NOTE: 30 FEET 4 INCH PVC PIPE, CAP, 2 COUPLINGS

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC8
20060306WS1
VERMILION GROVE

RIG # TH-60B

Run No.	CORE Cut	CORE Rec.	DRILLING FEET FROM	TO	Thick	LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	41.00	15.00	058.3		UNCONS sand w/gravel med gray		
			41.00	111.00	70.00	334		SANDY SHALE med gray		
			111.00	115.00	4.00	020		**COAL**		
			115.00	119.00	4.00	131		CLAYSTONE med gray		
			119.00	128.00	9.00	331		SANDY CLAYSTONE med gray		
			128.00	159.00	31.00	333		SANDY SHALE med gray w/sandstone strks - LIME NODULES		
			159.00	178.00	19.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			178.00	183.00	5.00	530		SANDSTONE med gray		
			183.00	206.00	23.00	334		SANDY SHALE med gray		
			206.00	212.50	6.50	020		**COAL**		
			212.50	215.00	2.50	331		SANDY CLAYSTONE med gray		
				215.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA			
DATE DRILLED		03-04-2006	
DATE COMPLETED		03-04-2006	
DRILLER	MICHAEL	HELPER	BRETT
SURFACE ELEVATION			
TOTAL DEPTH		215.00'	
CORE SIZE			
CASING DEPTH		43.50'	
NUMBER OF CEMENT BAGS		21	

LOCATION

SECTION : TWNSHP : RANGE : QUAD :
COUNTY : VERMILION
STATE : IL

LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : WSUC8
SECTION HOLE# LEASE

NOTE:

MAGNUM DRILLING SERVICES INC
DRILL LOG

WSUC9
20060306WS1
VERMILION GROVE

RIG # TH-60B

CORE			DRILLING			LITH. CODE NO.	BED	DESCRIPTION OF ROCK / NOTE	CORE GRAPH	CORE DESC.
Run No.	Cut	Rec.	FROM	TO	Thick					
				5.00	5.00	052.5		UNCONS silty or sandy clay tan or buff		
			5.00	12.00	7.00	058.6		UNCONS sand w/gravel red or brown		
			12.00	26.00	14.00	052.3		UNCONS silty or sandy clay med gray		
			26.00	41.00	15.00	058.3		UNCONS sand w/gravel med gray		
			41.00	111.00	70.00	334		SANDY SHALE med gray		
			111.00	115.00	4.00	020		**COAL**		
			115.00	128.00	13.00	331		SANDY CLAYSTONE med gray		
			128.00	159.00	31.00	333		SANDY SHALE med gray w/sandstone strks - LIME NODULES		
			159.00	178.00	19.00	533		SANDSTONE med gray w/shale strks - LIME NODULES		
			178.00	206.00	28.00	334		SANDY SHALE med gray		
			206.00	212.60	6.60	020		**COAL**		
			212.60	215.00	2.40	331		SANDY CLAYSTONE med gray		
				215.00		TD		TOTAL DEPTH		

HYDROLOGICAL DATA : Depth of Water :

DRILL HOLE DATA			
DATE DRILLED		03-04-2006	
DATE COMPLETED		03-04-2006	
DRILLER	MICHAEL	HELPER	BRETT
SURFACE ELEVATION			
TOTAL DEPTH		215.00'	
CORE SIZE			
CASING DEPTH		43.50'	
NUMBER OF CEMENT BAGS		21	

LOCATION

SECTION : ____ TWNSHP : ____ RANGE : ____ QUAD : ____
COUNTY : VERMILION
STATE : IL
LANDOWNER : C. LAMBERT
MAP NUMBER :
PROJECT AREA : VERMILION GROVE
DRILL HOLE : WSUC9 (SECTION / HOLE# / LEASE)

NOTE: